THE IMPACT OF ROAD DUST ON ARCTIC AQUATIC ECOSYSTEMS, NORTHWEST TERRITORIES, CANADA

By

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A thesis submitted to the Faculty of Graduate Studies in partial fulfillment of the requirements of the degree of

Master of Science

in

Earth Sciences

Brock University

St. Catharines, ON

ABSTRACT

The Canadian Arctic is currently undergoing rapid environmental and climatic changes. Resource development in northern regions also continues to expand, which requires more infrastructure such as roads. The Dempster Highway is a potential source for calcareous road dust since construction was completed in AD1979. Along the same timeline, the regional air temperatures began increasing, with the warming beginning around AD1970. Previous research indicates that dust from gravel highways has an impact on vegetation, and that the roadbed itself can alter near-surface permafrost temperature regimes. This research aims to employ paleolimnological methods to examine the potential impact of calcareous road dust on the aquatic ecosystems close to the Dempster Highway, as well as the possible effects from a warming climate. Lake sediment cores were taken from two impacted lakes adjacent to the highway (FM02 and FM04) and from one reference lake (FM06) located a far enough distance away that it is outside the range of dust transport. Through analyses of water chemistry, it was discovered that both the dust from the Dempster Highway and retrogressive thaw slumps in the surrounding area have an extensive impact on certain water chemistry variables (i.e. conductivity, pH, Ca^{+2}, etc.); However, elemental profiles of the sediment cores revealed no signal from calcareous road dust in lake FM02. The NPP exhibited a clear shift to genera that prefer both warmer and more humid climates, as well as increased nutrients, all products of regional warming and increased influx of calcareous road dust during construction of the Dempster Highway. This research will help the Department of Transportation and Department of Natural Resources in making regulatory decisions regarding new infrastructure in the Canadian Arctic.

ACKNOWLEDGEMENTS

Dr. Michael Pisaric

I would like to acknowledge my supervisor, Dr. Michael Pisaric, for allowing me to be part of such an interesting project. He gave me the opportunity to travel to the Northwest Territories, one of the most beautiful places in the world. The support and encouragement he provided throughout my master's degree is truly appreciated.

Dr. Joshua Thienpont

Additional recognition must go out to Josh for his assistance in the field along with his ability to answer many of the questions I had as a new master's student.

Steve Kokelj

Recognition also goes out to Steve for his continued interest in the project and his handy fieldwork skills that were much needed during all three of my field seasons.

Dr. Francine McCarthy, Dr. Kevin Turner and Dr. Roberto Quinlan

Many thanks are due for your knowledge, input and the suggestions that were put towards improving the quality of this thesis. Also, large thanks for answering the many questions I had along the way.

Cait Garner

Cait, where to begin! Firstly, thank you endlessly for the many hours spent in the lab helping me to completing the NPP processing and later the identification of the algal palynomorphs throughout my FM02 core, I can never thank you enough. Thank you for being an amazing friend, someone to vent to in times of stress and for keeping me grounded even when I wanted to fly away to a distant place. The memories made over the last three years, especially those at Lake George and at the cottage in Bobcaygeon, (Kawartha Lakes Winery, the Warsaw caves and of course the Blue Jays massive win over the Texas Rangers in October 2015) will never be forgotten.

The WEL at Brock University

This includes Drs. Michael Pisaric and Kevin Turner, Zach Harmer, Tyler Prince, Danny Hughes, Dana Harris, Cait Garner, Brent Thorne and Emily Ham. I am so thankful for getting to know each of you, and for your continued support over the last three years. Although the lab did not become "official" until last year, most of you have been with me every step of the way. The constant reminder that I am not alone in graduate school, which at times became a little much, was something that got me through the harder times. I am so appreciative of every single one of you, and I am sure we have made friendships that will last a lifetime. You all rock and keep up the amazing work!

Cory

There are not enough words to express how thankful I am that you stood by me through this entire journey. Your love and support is what got me through the hardest of times. At every chance you got, you had me laughing to make sure that I did not go completely insane over my research. Thank you for always being at home with a massive glass of wine or a beer, already poured, on my toughest days. I feel like the luckiest girl in the world, being able to spend the rest of my life with you. I love you to the moon and back!

Lola, Sophie and Misfit

To my favourite kitties, and the best kitties in the world! Your snuggles and purrs were always the best thing to come home to after a long day in the lab or a long day of writing. Although you were a huge distraction at times, you have brought so much joy to my life over the last three years and I could never thank you enough!

Rachel

I am so grateful that you decided to take Dr. Francine McCarthy's limnogeology class during my first year of grad school; without it, my heart would not be as full as it is in this moment. Over the last three years you have been my voice of reason (which I needed a lot of the time) and you always knew what to say to keep me grounded. The memories made with you and Cait will live on forever, even if you have to stay out in Calgary for another three years. I love you, cannot thank you enough for being there with me every step of the way, and can't wait for you to stand beside me when I marry my bestfriend!

Teresa

What is there to say other than a girl cannot go through graduate work without her bestie. I'm so happy that we have become closer over the last three years and can't wait to see where our journeys take us. Whether it was Kully's pizza, wings and beers, cider and nachos at the Feathery, or ice cream outings at Avondale Dairy Bar, those nights out and our endless conversations helped keep me sane. I love you and can't wait to make many more memories with you by my side!

Karen and Peter Gunter, My Parents

A very special thanks goes out to my parents. Thank you for always believing in me, even when I did not believe in myself and for pushing me to excel beyond what I ever thought possible. A special thanks to my dad for all the long hours spent editing every last word of ever paper I ever wrote, including most of this thesis; I doubt any of my papers would have been even half as good without you. I love you both so much.

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LIST OF ACRONYMS

Ag	silver
Al	aluminum
As	arsenic
a.s.l	above sea level
Ba	barium
Be	beryllium
BOD	biochemical oxygen demand
Ca	calcium
Cd	cadmium
Cl	chlorine
cm	centimetre
Co	cobalt
Cr	chromium
Cs	cesium
Cu	copper
DN	dissolved nitrogen
DOC	dissolver organic carbon
DP	dissolved phosphorus
F	fluorine
Fe	iron
HCl	hydrochloric acid
HF	hydrofluoric acid
K	potassium
Li	lithium
LOI	loss on ignition
m	metre
Mg	magnesium
mg/L	milligrams per litre
Mn	manganese
Mo	molybdenum
N	nitrogen
Na	sodium
NH_3	ammonia
Ni	nickel
NO_2-N	nitrite
NO_3-N	nitrate
NO_3/NO_2-N	nitrate-nitrite ratio
NPP	non-pollen palynomorph
NTU	nephelometric turbidity units
OC	organic carbon
OP	organic phosphorus
P	phosphorus
Pb	lead
Pb^{210}	lead-210

pH	measure of the –log(H+)
Rb	rubidium
Sb	antimony
Se	selenium
Si	silica - reactive
SO_4	sulphate
Sr	strontium
TDS	total dissolved solids
Ti	titanium
Tl	thallium
TN	total nitrogen
TOC	total organic carbon
TP	total phosphorus
TSS	total suspended solids
U	uranium
V	vandium
Zn	zinc
μg/L	microgram per litre
μS/cm	microSiemens per centimetre

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Chapter 1

Overview and Objectives

1.1 Introduction

The Canadian Arctic is currently undergoing rapid environmental and climatic changes. Coupled with these rapid changes, resource development in northern regions continues to expand, requiring more infrastructure such as roads. Since 2002, over 103 infrastructure projects have been funded within the Northwest Territories, amounting to ~30 billion dollars of infrastructure spending (Infrastructure Canada, 2016). The budget for 2016 for public transportation alone in the Northwest Territories will amount to over $6 billion (CA) (Infrastructure Canada, 2016). Although development within the North can be seen as advancement, it could have great implications on the surrounding ecosystem. With increasing resource development and population in the Canadian North, the need for all-weather road infrastructure will increase.

Research indicates that dust from gravel highways can negatively impact roadside vegetation. Farmer (1993) suggests that the most damaging effects of road dust on vegetation have occurred in the high Arctic. This could be due to the fact that the vegetation found in the high Arctic is sensitive to environmental and climatic change. For example, moss biomass along the edges of gravel highways has been found to decrease continually over time and is often replaced by graminoid populations as a result of dust loading (Walker and Everett, 1987; Auerbach et al., 1997; Myers-Smith et al., 2006). Myers-Smith et al. (2006) noted a decrease of 130 g/m^2 in moss biomass within 5 m of the Dalton Highway, Alaska, and a reciprocal increase of 80 g/m^2 in graminoid biomass between 1989 and 2002. The decrease in moss biomass, specifically *Sphagnum,* was due to the increase in pH levels of the soils along the gravel highway embankments, attributed to the addition of calcareous road dust (Auerbach et al., 1997; Spatt, 1978). In a series of other studies, water extracted from *Sphagnum* samples collected from close to a gravel highway (within 25 m), had increased total conductivity, pH and Ca^{+2} compared to samples located 125-250 m from the Dalton Highway (Spatt, 1978; Spatt and Miller, 1979). Research by Leadley et al. (1996) suggested that dust could potentially impact the environment as far as 600 m from gravel highways. Myers-Smith et al. (2006) found that the disturbance effects (e.g. increases in pH, modification of the microenvironment and ecosystem processes, altered canopy structure, changes in soil chemistry, fluctuations in microbial decomposition and soil thaw) were minimized beyond 400 m. The decrease in disturbance effects could be due to lower levels of dust, however Leadley et al. (1996) and Myers-Smith et al. (2006) suggested that areas 400-600 m from the Dalton Highway might have had a longer ecosystem reaction time compared to the areas closer to the highway.

A recent study by Gill et al. (2014) found that shrub populations and canopy cover increased at sites closest to the Dempster Highway, due to increases in the temperature and pH of the soil, and nutrient availability. Areas with tall shrub growth also had increased snow accumulation. Snow protects the tall shrubs from harsh winter winds, increases soil moisture in roadside areas, and slows heat escape from the ground, increasing ground temperatures in the upper permafrost and the active layer (Zhang and Stamnes, 1998; Lantz et al., 2009). These conditions are favourable for tall shrub growth and can help create a shift from mosses and lichens to tall shrubs along the sides of gravel highways (Sturm et al., 2001).

Dust from gravel highways in the Arctic also has detrimental impacts on the surrounding near-surface permafrost temperature regimes. Marchildon et al. (2012) and Gill et al. (2014) concluded that all-weather roads create feedback cycles of disturbance that induce ground temperature changes. This feedback cycle indicates that as dust deposition from the road increases, soil pH and nutrient availability also increase. Areas up to 25 m from the road experience increased snow accumulation due to maintenance of the road and the ability of tall shrubs to catch drifting snow. With the changes in vegetation and increases in the snow pack, the active layer is more insulated and leading to warmer permafrost conditions alongside the highway (O'Neill and Burn, 2015; O'Neill et al., 2015). The increase in the active layer thickness due to insulation usually occurs within the first 10 m from a gravel highway (Walker and Eevrett, 1987; Auerbach et al., 1997). This positive feedback accelerates permafrost thaw.

While the impacts of road dust from northern gravel highways on terrestrial ecosystems are well known, the impacts on Arctic aquatic ecosystems have not been extensively studied. The impacts on aquatic ecosystems can be assessed using non-pollen palynomorphs (NPP) as a biological proxy (Komarek and Jankovska, 2001; van Geel, 2001; Jankovska and Komarek, 2000). NPP have specific ecological preferences that allow them to be used as bio-indicators. Previously, NPP have proven to be good indicators of environmental and anthropogenic changes (Volik, 2014; Medeanic et al., 2008), water quality (Danesh et al., 2013), and trophic levels within lakes (Drljepan et al., 2014). With this information, NPP can be identified and numerated, and in conjunction with water chemistry data and physical sedimentology, the health of aquatic ecosystems before and after the construction of the Dempster Highway can be determined.

The lack of research on the impacts of dust loading on aquatic ecosystems limits the capacity for informed regulatory decisions regarding future development, such as the Inuvik to Tuktoyaktuk highway. Information on the impacts of dust loading on water chemistry, aquatic organisms and physical sedimentology could be used to inform agencies such as the Department of Transportation and the Department of Environment and Natural Resources about the potential impacts dust loading could have on aquatic ecosystems in the vicinity of the Inuvik to Tuktoyaktuk highway corridor.

1.2 Objectives and Research Questions

The main objective of this research is to compare water chemistry from a suite of small impacted lakes located close to the Dempster Highway and reference lakes located as much as 30 km from the highway and presumably beyond the reach of dust deposition. Element profiles will be examined from sediment cores taken from two small lakes located within close proximity to the Dempster Highway and one reference lake located ~30 km away in order to determine differences before and after highway construction. A sediment core from FM02, located ~50 m from the Dempster Highway, will be examined for NPP. NPP will be identified and numerated for segments of the lake sediment core to cover a period of time both before and after highway construction. The following research questions will be examined:

1. Does dust loading from the Dempster Highway alter water chemistry (i.e., pH, conductivity, concentration of major ions) in lakes located within close proximity to the highway compared to those farther away?

2. Does the presence of heavy metals and other elements in lake sediment profiles change after the construction of the Dempster Highway?
3. What impact has the construction of the Dempster Highway had on the NPP assemblages within the impacted lake (FM02)?

1.3. Structure of Thesis

This thesis consists of six chapters. Chapter one has given background information as well as context for the thesis. Chapter two is a review of dust deposition in the Arctic, sediment cores and NPP as indicators of environmental change. Chapter three describes the study site and methodologies within the field and the laboratory. Chapter four presents the results of the research, including analyses of water chemistry, physical sedimentology and algal palynomorph data. Chapter five discusses the effects of road dust from the Dempster Highway on aquatic ecosystems and the potential contributions this can make to regulatory decisions related to the current construction and future maintenance and management of the Inuvik to Tuktoyaktuk highway corridor. Chapter six summarizes the research results, presents conclusions, and offers suggestions for future research.

Chapter 2

Literature Review

2.1 Introduction

In order to complete a comprehensive study to determine the impacts of dust loading on Arctic aquatic ecosystems, there needs to be an understanding of: (1) resource development and infrastructure within the Canadian Arctic, (2) the impacts of dust on vegetation and near-surface permafrost close to gravel highways, and (3) how sediment cores and non-pollen palynomorphs (NPP) act as indicators of environmental change. This chapter will review the current and past literature, along with the methodologies used in this thesis.

2.2 Climate Change in the Canadian Arctic

The Arctic is undergoing rapid environmental and climatic changes. Some of the impacts associated with climate change include: increasing global mean temperatures, decreases or abrupt changes in precipitation, rising sea levels and melting of glaciers (Shindell, 2014). Evidence currently exists that links this increase in human activities (such as the increased use of fossil fuels or industrial practices) to impacts that are associated with climate change. Unfortunately for the Canadian Arctic, climate change is much more pronounced, with temperatures rising at twice the global rate according to McBean et al. (2005). The most notable changes in mean annual ground temperature are occurring in the western Arctic and are most extreme during the winter months (Beilman et al., 2001; Hengeveld et al., 2005). As both air and ground temperatures begin to increase, they can have detrimental effects on the permafrost across the region. Even small increases in ground temperatures can have drastic impacts on the continuous permafrost, as it is a very sensitive indicator of environmental and climatic changes (Natural Resources Canada, 2016).

Environment and Natural Resources Canada (2015) has noted a 3°C increase in the average temperature at Inuvik over a 54-year period (1958-2012). Even larger temperature increases are noted for the cold seasons (5.2°C). While temperatures have increased at Inuvik, precipitation has decreased slightly since 1958. Burn and Kokelj (2009) plotted temperature data at Inuvik from 1935-2006 and noticed that between 1996 and 2006 the temperature at Inuvik has increased more rapidly and the increase has been more significant than what has been noted in previous periods. Since 1970, Burn and Kokelj (2009) found that the annual temperatures have increased by approximately 2.5°C in Inuvik.

Temperatures in the Canadian Arctic are projected to increase over the next 100 years (Figure 2.1). Even with the minimum change there is a projected increase in mean annual temperatures in the Canadian Arctic of ~4°C (Natural Resources Canada, 2016b). As air temperature increases, it causes subsequent increases in the ground temperatures, which can facilitate the thawing of permafrost. The thawing of permafrost can in turn impact the stability of all-weather highways across the region and the banks of lakes, leading to the generation of retrogressive thaw slumps.

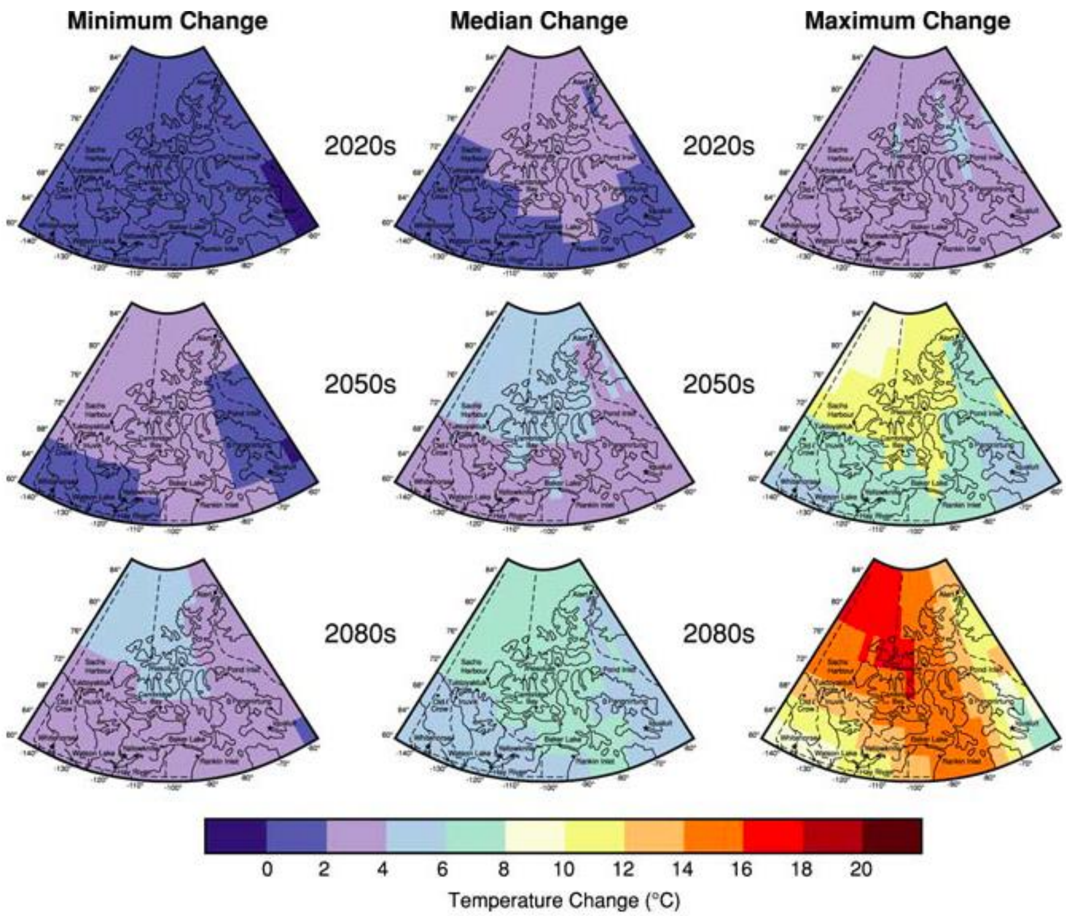

Figure 2.1 Projected changes for mean annual temperatures in the Canadian North. Even with minimum projected change, within the next 100 years, there is an increase of ~2°C to ~6°C in the northern areas, from Natural Resources Canada (2016b).

2.2.1 Permafrost and Retrogressive Thaw Slumps

Permafrost is known as ground (soil, rock, ice and organic materials) that remains at or below 0°C for more than two consecutive years (Natural Resources Canada, 2016). The Peel Plateau is considered a continuous permafrost zone, meaning that more than 90% of the surface is underlain by frozen ground (Figure 2.2). Most of the Western Arctic is underlain by continuous permafrost that can be as thick as 300 m (Burn, 2002). Along the Peel Plateau, and more specifically along the Dempster Highway, the permafrost temperatures vary significantly between the middle of the highway and up to 150 m away from the toe embankment (O'Neil et al., 2015a; Idrees et al., 2015). O'Neil et al. (2015) found that the permafrost is degrading at four out of five of their impacted sites (within 5 m of the highway). The temperature of the permafrost at 5 m depth at these four sites ranged from -1.3°C to 0.0°C, whereas at the two control sites the permafrost at the same depth recorded temperatures between -1.8°C to -2.6°C. Although permafrost is degrading throughout the Peel Plateau due to climate change, projections for permafrost degradation show that complete thaw is unlikely to occur before 2100 (Figure 2.3). The most northern areas of the Canadian Arctic are not expected to experience any thaw until after 2100 according to Romanovsky (2008). The United Nations Environment Programme (UNEP) (2016) suggests that the active layer thickness in some permafrost regions could increase to ~200 cm or more by 2100 and that only areas in the most southern regions of Canada and potentially through the northern prairie provinces will see complete permafrost thaw by this time. While the climate change scenarios may not indicate that there will be thawing of the permafrost by 2100 in the Canadian Arctic,

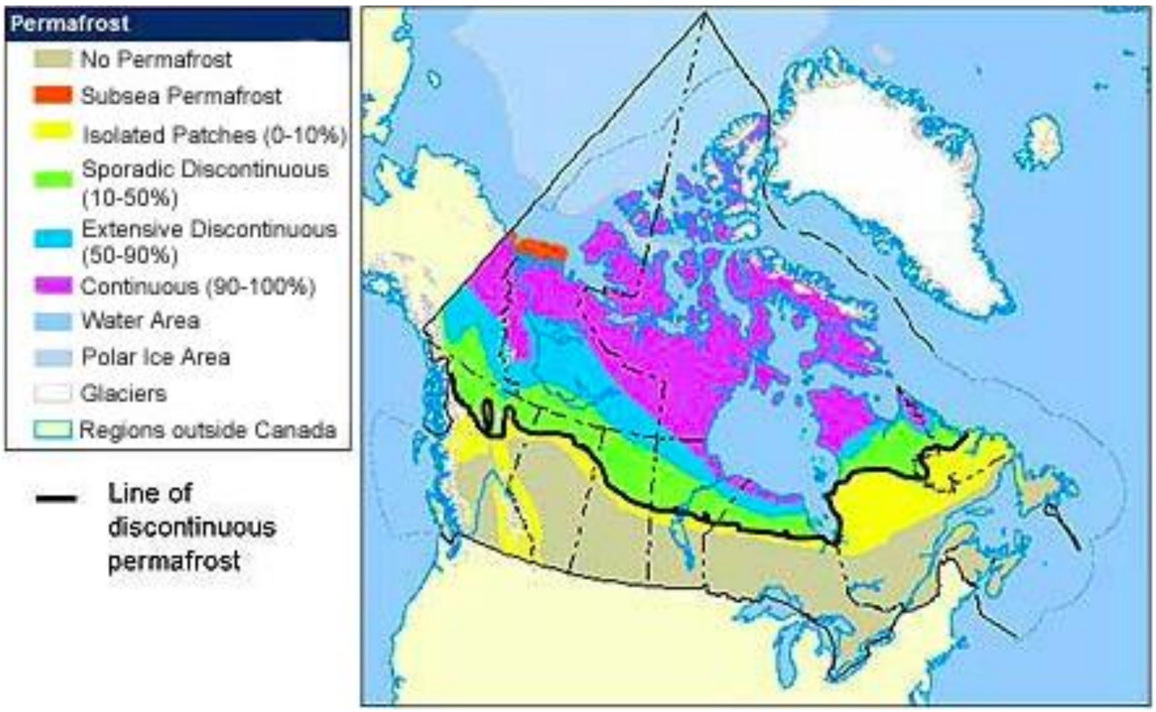

Figure 2.2 Permafrost zones of Canada as well as the southern limit of the line of discontinuous permafrost (bold black line). Note that the northernmost area along the border of the Northwest Territories and the Yukon Territory, where the study site is located, the permafrost is considered to be continuous (90%-100%), in the top right corner of the map (from Environment and Climate Change Canada, 2008).

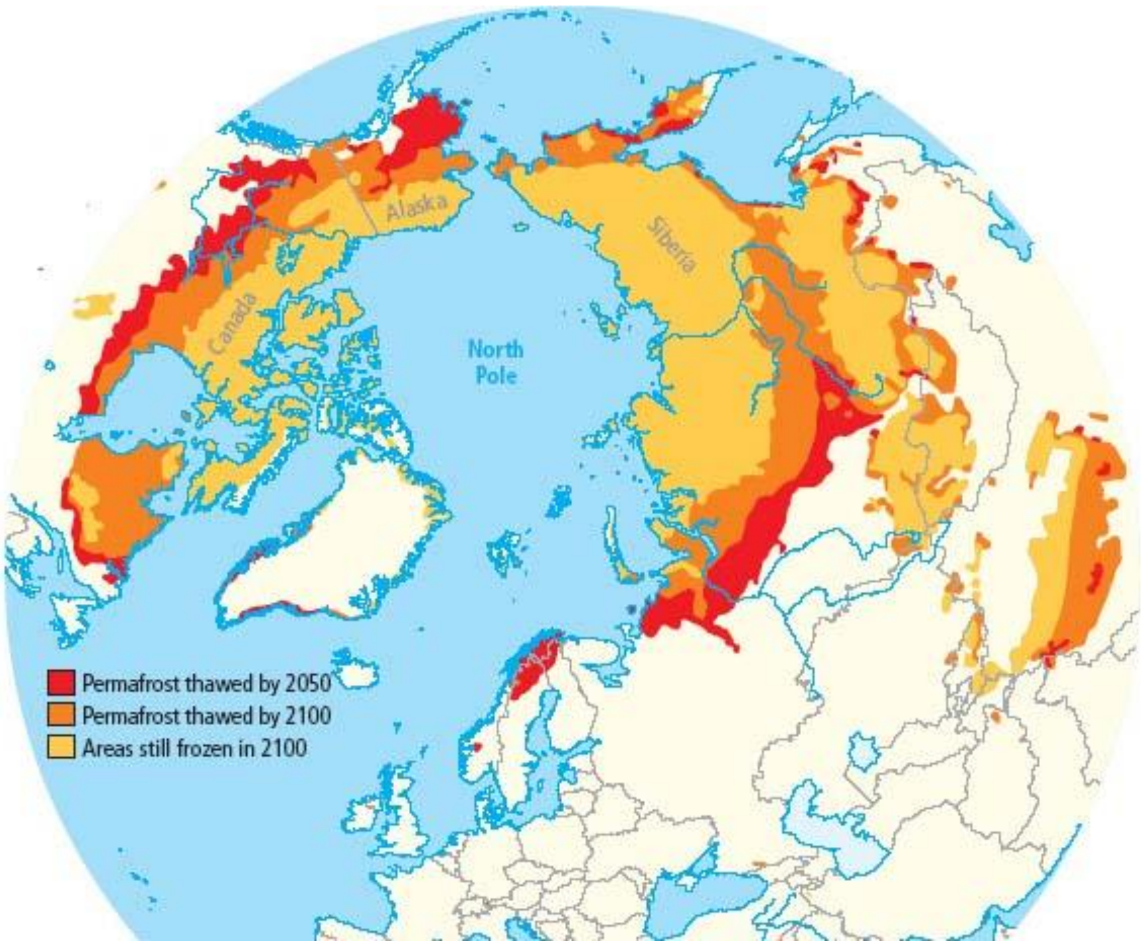

Figure 2.3 The predicted extent of permafrost thaw across the circumpolar Arctic by the year 2050 and 2100. Most northern regions of Canada will still be frozen by 2100, but very close to the Peel Plateau there are some areas that could be thawed by this time. (from Romanovsky, 2008).

results from O'Neill et al. (2015) show that some permafrost temperatures within the first 5 m away from the Dempster Highway are already at 0.0°C. If the temperatures continue to rise, the permafrost at 5 m depth could warm sufficiently to begin to thaw in areas along the Dempster Highway much before 2100.

The degradation or thawing of permafrost is mostly driven by the increases in global mean temperatures that are being seen across the Canadian Arctic. As permafrost degrades, it creates a thermokarst-dominated landscape. Thermokarst landscapes include the widespread failure, instability or erosion of the surface as a result of permafrost thawing (French, 2007). There are many different types of thermokarst features throughout the Canadian Arctic landscape and they are dependent on many factors, such as: permafrost and ground ice conditions, surrounding vegetation, hydrology, relief and soil texture (Jorgenson and Osterkamp, 2005; Belshe et al., 2013). When thermokarst forms on the hillslopes, it can lead to thermal erosion or slumping that can have major effects on the surrounding ecosystems (Kokelj and Jorgenson, 2013; Jensen et al., 2014). In this type of thermokarst environment, the active layer can be stripped, which leads to the exposure of the underlying frozen ground. This underlying frozen ground is susceptible to thaw and a retrogressive thaw slump may be formed.

A retrogressive thaw slump is a thermokarst feature that is one of the most rapidly erosive in periglacial environments (French, 2007). When a thaw slump is active it has a horseshoe shape (Mackay, 1996) with a retreating headwall, slump floor and an evacuation channel (Figure 2.4). The material released by retrogressive thaw slumps can alter the physical and chemical parameters of nearby aquatic ecosystems that receive runoff from these disturbances (Kokelj et al., 2013; Malone et al., 2013).

Figure 2.4 The anatomy of a retrogressive thaw slump. Important components of the thaw slump are indicated, including the headwall (the area where there is a steep incline), the slump floor (where the debris gathers as the slump erodes), and the evacuation channel (where the debris continues to and where it further erodes the channel). Also depicted here is a scar from a former slump in the top right hand corner. Photo from Lacelle et al. (2010).

As disturbance of the retrogressive thaw slump occurs, materials flow into the lacustrine environments as surface runoff. A study completed by Kokelj et al. (2005) determined changes in water chemistry parameters such as Ca^{2+}, Mg^{2+}, and SO_4^{2-} between 11 lakes impacted by slumps and 11 control lakes. The differences in the mean concentrations for Ca^{2+} were quite striking, as the disturbed systems had a value of 72.6 mg/L compared to the undisturbed systems that had an average of 9.2 mg/L. Magnesium and sulphate from disturbed systems averaged 26.8 mg/L and 208.2 mg/L, respectively and 3.6 mg/L and 11.1 mg/L, respectively, for undisturbed lakes. Overall, Kokelj et al. (2005) found that if even 2% of the lake catchment is impacted by a retrogressive thaw slump it is likely that the water chemistry will be affected and will continue to be affected for decades following the initial disturbance. Kokelj et al. (2009) conducted a much larger study that looked at over 60 lakes, half of which were disturbed and half that were undisturbed catchments. Their results were similar to their earlier study and concluded that ion concentrations are directly impacted by retrogressive thaw slump activity.

2.3 Resource Developments and Infrastructure in the Canadian Arctic

As the Canadian Arctic warms, sea-ice cover has declined, which opens up new opportunities for resource development in these areas (Rigor et al., 2002; Rigor and Wallace, 2004 Drummond, 2006; Prowse et al., 2009; National Snow and Ice Data Center, 2016). The expansion of resource development will be mostly within the context of marine transport, but some emphasis will also be placed upon inland mining and oil operations and their connections to the surrounding communities (Prowse et al., 2009).

Additional concerns with increasing air and ground temperatures in northern regions are the loss and/or diminished quality of seasonal roads (roads composed of snow and ice that are only available during the winter months) in the Northwest Territories. Stephenson et al. (2001) predict that by 2050 the amount of accessible winter road area in the Canadian Arctic will decrease by approximately 13%. Currently, resource development in the Northwest Territories relies heavily on the presence of seasonal roads. There are few all-weather highways that connect remote areas of the Northwest Territories. Many northern communities also rely on seasonal roads for resupply of fuels, food, and other goods (Government of Northwest Territories, 2016). The construction of more all-weather highways is expected to increase in the coming years as resource development and populations continue to expand (Prowse et al., 2009).

As of April 7th, 2016 the all-weather gravel highway being built between Inuvik and Tuktoyaktuk as an extension of the Dempster Highway was connected (Barton, 2016). This highway links the community of Tuktoyaktuk to the Yukon and provides southern Canada with all-season road access to the Arctic Coast. Upon completion, the highway will be 138 km in length and will add approximately $783 million to Canada's gross domestic product (GDP) (Inuvik to Tuktoyaktuk Mackenzie Valley Highway, 2016). This highway will be very important to the community of Tuktoyaktuk, as it is normally only accessible by boat during the summer months and by ice roads in the winter (Inuvik to Tuktoyaktuk Mackenzie Valley Highway, 2016).

Unfortunately, due to increasing air and ground temperatures throughout the Canadian Arctic, the use of seasonal roads can become unreliable. This is one of the main reasons that there is a high demand for the construction of more all-weather highways.

Currently, research indicates that there are extensive negative impacts of road dust from gravel highways on both vegetation (Auerbach et al., 1997; Walker and Everett, 1987; Spatt, 1978; Spatt and Miller, 1979; Myers-Smith et al., 2006; Farmer, 1993; Gill et al., 2014) and near-surface permafrost (Marchildon et al., 2012; Gill et al., 2014; Idrees et al., 2015; O'Neill et al., 2015).

2.4 Impacts of Dust Loading on Vegetation

A number of studies have looked at the effects of dust loading on vegetation along all-weather highways in the Canadian Arctic. Research has concluded that areas directly beside gravel highways have seen large decreases or complete disappearance of mosses such as *Sphagnum* (Myers-Smith et al., 2006). These areas have been replaced with graminoid populations or tall shrubs. *Sphagnum* is a crucial component to Arctic ecosystems as it helps the ground around gravel highways remain cool, which helps keep the active layer thickness to a minimum and prevents the thawing of permafrost. With significant loss of mosses close to gravel highways, it promotes the growth of taller shrubs and graminoids, which can enhance snow accumulation and insulation at the edges of the road (Gill et al., 2014). Understanding the impact of dust loading on vegetation is crucial in determining the overall impact on an ecosystem. It is also crucial to understand the impacts of road dust on vegetation at the roadside more specifically because the types of vegetation around the lakes can impact the health and diversity of the aquatic communities.

Everett (1980) concluded that calcareous road dust impacts areas within 300 m of a gravel highway. Similarly, Auerbach et al. (1997) observed the impacts of dust from the

Dalton Highway, Alaska to be greatest between 2-525 m from the road. Auerbach et al. (1997) studied both acidic and basic soils to determine whether or not dust impacts are more detrimental to soils of a specific pH. Soils with more acidic pH values saw the largest changes (from ~ 4 to 7.3 ± 0.07) due to the introduction of calcareous dust (Auerbach et al., 1997). The acidic zones also saw the largest decrease in mosses such as *Sphagnum,* which grow in more acidic soils. Species richness in areas where pH changed due to dust loading decreased by more than half within 2 m of the road compared to 100 m away (Figure 2.5) (Auerbach et al., 1997). Walker and Everett (1987) also noted large decreases in *Sphagnum,* as well as other acidophilus mosses within 10 to 20 m of the Dalton Highway. Walker and Everett (1987) suggest caution is needed in areas that are dominated by *Sphagnum* as they have proven to be especially sensitive to the effects of road dust.

Spatt (1978) and Spatt and Miller (1979) examined the changes in water in the leaves of *Sphagnum* between 25-200 m from the Dalton Highway, Alaska. The water was tested for pH, conductivity and Ca^{2+} levels. The conclusion was that *Sphagnum* within 25 m of the road had between 4-27 ppm of Ca^{2+} and samples from 200 m recorded values of <1 ppm of Ca^{2+}. All samples within close proximity to the highway showed increases in pH (to more basic levels) and total conductivity. White and Broadley (2003) explain that vegetation can easily suffer from Ca^{2+} toxicity if the amount of Ca^{2+} exceeds that of the needs of the plant and could result in the inhibition of seed germination or a reduction in the growth rate of the plant. Spatt (1978) describes the importance of looking into changes in pH, conductivity and Ca^{2+} concentrations in aquatic systems that would likely see additions of calcareous road dust.

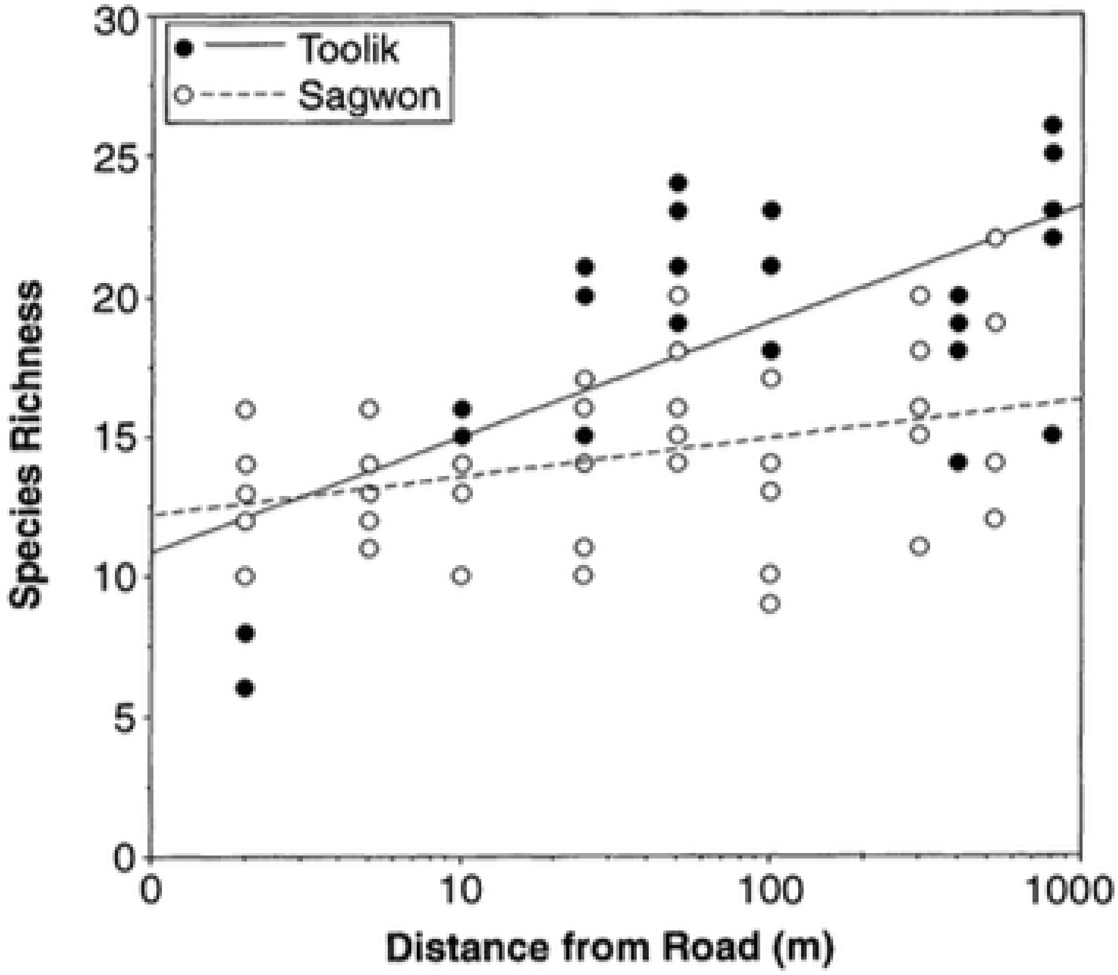

Figure 2.5 Species richness vs. log of distance from the road at two study sites along the Dalton Highway, Alaska (from Auerbach et al., 1997).

A more recent study regarding the effects of calcareous road dust on vegetation has determined the change in grams per meter (g/m) of *Sphagnum* and graminoid biomass near roadsides. Myers-Smith et al. (2006) examined the tundra between 2-800 m from the Dalton Highway, Alaska and found that between 1989 and 2002 there was a 130 g/m decline in moss biomass within 5 m of the road and an 80 g/m increase in graminoid biomass. In addition, within 5 m of the Dalton Highway the graminoid dominance was approximately 80%, whereas in areas with undisturbed tundra the range was 30%. Along with the loss of mosses and increase in graminoid populations, Myers-Smith et al. (2006) also determined that the zone of tundra disturbed by road dust along the Dalton Highway had increased between 1989 and 2002, possibly due to increasing traffic along the highway or increases in wind speeds due to changing climatic conditions.

Gill et al. (2014) examined the vegetation, soils and near-surface ground temperatures in tall and dwarf shrub tundra within close proximity to the Dempster Highway (~15 m) and at more distant, undisturbed sites (~500 m). Overall, there was a clear increase in alder shrub growth in close proximity to the Dempster Highway. Tall shrubs near the highway experienced increased nutrient availability, greater organic layer thickness and thicker snow packs. The alder shrubs thrive in areas that have inputs of calcareous road dust because their growth is enhanced by micronutrients such as Ca^{2+}, S^{-2} and Mg^{2+}, which are all common in the gravel and dust along the Dempster Highway (Strum et al., 2001; Lantz et al., 2009). Gill et al. (2014) proposed the development of an ecological feedback in tundra systems as a result of dust loading along gravel highways. This ecological feedback is caused initially by changes in vegetation, which then alters the snow pack, active layer thickness and permafrost temperature, which contributes to further growth of alder shrubs along the roadside.

The most damaging effects of road dust have been seen in high Arctic systems, most likely due to the fragility of vegetation types such as *Sphagnum* to small changes in soil pH, moisture content and temperature (Farmer 1993). It is clear that the dust from gravel highways has significant impacts on the type of vegetation that will be found at the roadside. The relationship between the loss of *Sphagnum* or other mosses and increases in graminoid populations is evident within multiple studies. Also, the noted increase in alder shrub growth, specifically along the Dempster Highway, demonstrates that dust loading can have affects on vegetation within close proximity to gravel highways. As the vegetation changes along the road, it also promotes a positive feedback cycle that has been known to increase active layer thickness and the thawing of permafrost at roadside areas.

2.5 Impacts of Dust Loading on Near-Surface Permafrost

Permafrost thaw and increases in active layer thickness are occurring throughout the Canadian Arctic. Several studies have described the impacts specific to dust loading along gravel all-weather highways on near-surface permafrost temperature regimes. Research currently suggests that changes in vegetation promote increases in active layer thickness and thaw depth of permafrost within close proximity to gravel highways (Auerbach et al., 1997; Gill et al., 2014; O'Neill et al., 2015). Areas that lack vegetation along roadsides can experience noticeable increases in active layer thickness and permafrost thaw depth if the reflectivity (albedo) of the surface changes (Walker and Everett, 1987).

Most studies examining the impacts of road dust on vegetation also surveyed the impacts on the surrounding permafrost. For example, Auerbach et al. (1997) noticed an increase in active layer thickness near the Dalton Highway, Alaska. They attributed this increased thickness in the active layer to changes in albedo, since there was earlier snowmelt at the roadside. In addition, increased snowpack creates insulation at the side of the road during the cold seasons, increasing the active layer thickness. The vegetation changes that were noted by Auerbach et al. (1997) included an increase in graminoid biomass and also some deciduous shrubs. The change from shorter types of vegetation, such as *Sphagnum* mosses, to taller deciduous shrubs or graminoids promoted increased snow accumulation along the roadside (Marchildon et al., 2012; Gill et al., 2014). With increased snow accumulation, there was an increase in the insulation at these sites during the colder months. Increased insulation lengthens the period it takes for the active layer to re-freeze each season. Also, as the active layer begins to thicken and permafrost begins to thaw, there will be increased moisture in the soil, which could lead to a later re-freeze in the fall as more latent heat is stored in the soil at this time. Consequently, during the summer months the active layer thickens as insulation is enhanced by heat generated from the road and the tall shrub or graminoid populations (O’Neil and Burn, 2015).

A more detailed explanation in the development of ecological feedback that is present along the sides of all-weather highways can be seen in work done by Gill et al. (2014) and Marchildon et al. (2012). The impacts of both construction and maintenance of the Dempster Highway promote ecosystem processes that generate feedbacks between the biotic and abiotic conditions in order to enhance both snow accumulation and dust deposition over time, which enhances the effects on vegetation communities and soil properties. Gill et al. (2014) determined that in areas of increased tall shrub dominance, there was increased snow accumulation and subsequent changes in ground temperatures and soil chemistry. Since these changes are favourable to tall shrubs (Strum et al., 2001) these conditions further promote the growth and recruitment of shrubs while decreasing *sphagnum* populations due to higher pH in the soil (Figure 2.6). This feedback system increases the active layer thickness and thawing of permafrost because the taller shrubs trap more snow leading to an insulating effect, which then delays the re-freezing of the active layer during the winter months.

There have also been direct permafrost temperature measurements completed along the Dempster Highway. O'Neill et al. (2015) measured ground temperatures at five embankment toe locations and two control sites. The recorded temperatures at ~5 m depth were higher at the embankment toe (5 m to 8 m) than the control sites (50 m and 150 m). Measurements of permafrost temperatures near the embankment toe were between -2.2 and 0.0°C, while those at the control sites ranged from -2.6 to -1.8°C. O'Neill et al. (2015) also found that the permafrost was degraded at four of the five embankment toe locations and the thaw depths at these degraded sites were >1 m. The main reason for the permafrost degradation was increased ground temperatures as a result of enhanced snow accumulation (most likely due to increased shrub height and density as explained in Gill et al. (2014)). Idrees et al. (2015) also monitored permafrost conditions along the Dempster Highway using boreholes (~10 m in depth) in the highway centerline, the embankment toe and at control sites with undisturbed ground.

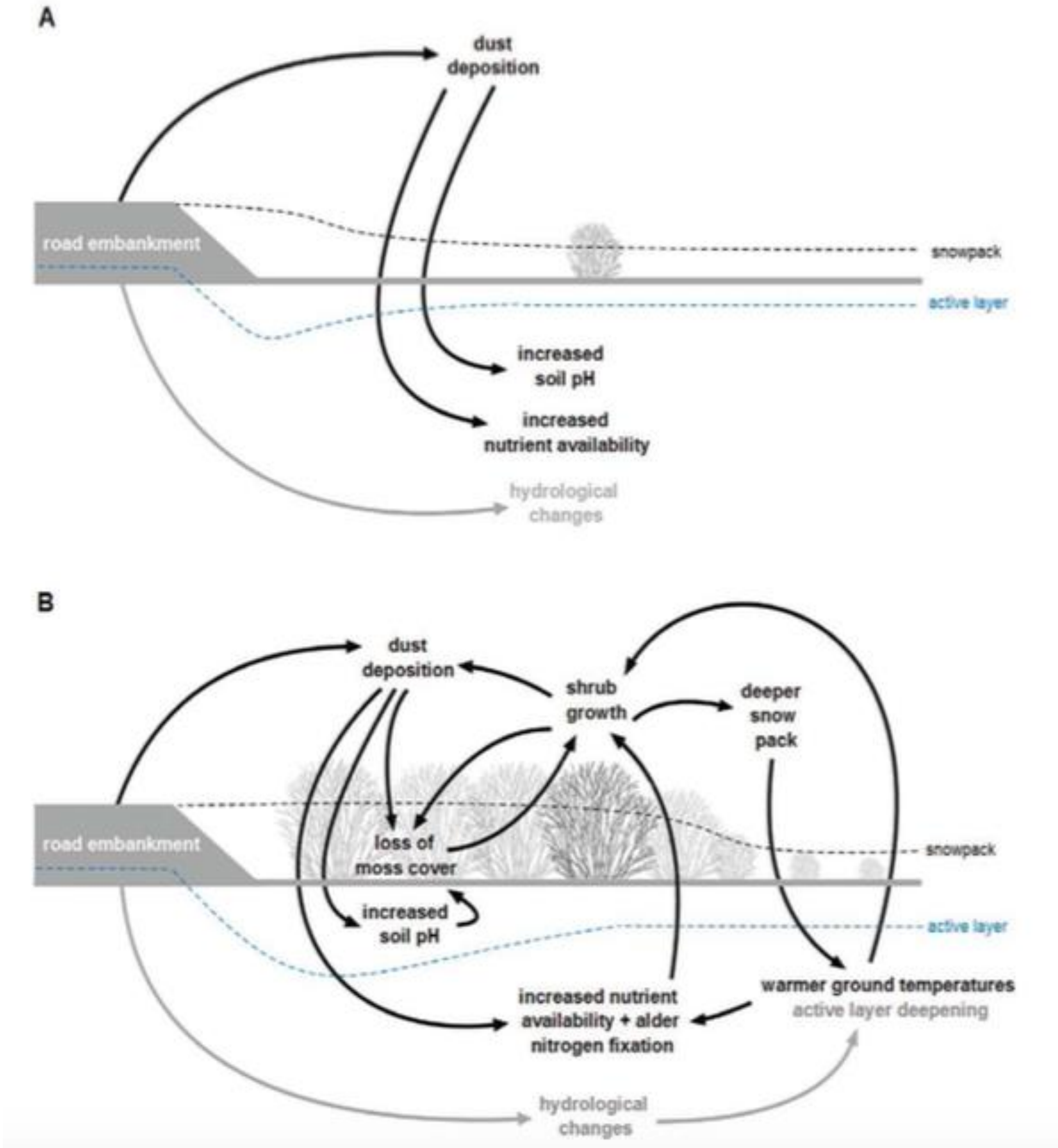

Figure 2.6 Conceptual models illustrating how construction and maintenance of a gravel highway leads to the development of ecological feedbacks in tundra ecosystems. (A) Directly after gravel highway construction. (B) 35-years after construction. Black text and arrows are indicative of changes that were seen by Gill et al. (2014) and grey arrows and text are hypothesized by Gill et al. (2014) or known to have occurred in other studies.

The embankment toe was found to have the warmest temperatures at every site. The highway centerline was the coldest of all areas, which could be due to the gravel pad that exists underneath the Dempster Highway to keep the ground cool, or because the snow along the highway is continuously removed during the colder months so the cold air temperatures can effectively penetrate deep into the ground. In conclusion, they found that the permafrost below all embankment toe sites was degrading, but that the permafrost underneath the center of the highway has slightly aggraded.

Past research has determined there are impacts associated with dust loading on both vegetation and permafrost along all-weather highways in the Arctic. However, there is an obvious research gap in understanding how dust from all-weather highways might impact nearby lakes and ponds. Some of the next steps include: using lake sediment cores as indicators of environmental change by examining non-pollen palynomorphs (NPPs) preserved in the lake sediment cores, analysing the organic content in lakes through using the loss-on-ignition (LOI) method, using statistical analysis on water chemistry parameters to determine impacts of calcareous road dust on the water column, and use of the ITRAX X-ray fluorescence scanner as a record of element intensity changes in lake sediment cores through time.

2.6 Analysis of Aquatic Ecosystem Health

Many types of environmental proxy data can be retrieved from lake sediment cores including physical, chemical and biological proxies (Smol, 2008). Each proxy can aid in the determination of changes in the environment over time. Aquatic ecosystem health should be assessed through a multi-proxy study. Such a study could include the use of lake sediment cores as an indicator of environmental changes. In each sediment core several factors can be examined to determine the state of the environment. NPP processing and identification can determine past environmental conditions, loss-on-ignition can determine organic and carbonate content throughout a core, and the ITRAX X-ray fluorescence core scanning system can provide elemental profiles for lake sediment cores.

Paleolimnological techniques allow us to look at changes in the environment such as climate warming, cultural eutrophication, effects of anthropogenic changes, and effects of atmospheric deposition. Lake sediment cores are relatively easy to acquire and they can provide a depth-time profile.

NPPs are good paleoenvironmental indicators because each species has specific ecological preferences (Riddick et al., 2016). This allows them to be used in determining changes in lake ecology over time (Komarek and Jankovska, 2001; van Geel, 2001; Jankovska and Komarek, 2000).

2.6.1 Non-Pollen Palynomorphs as Indicators of Environmental Change

Green algal palynomorphs are common in pollen slides that have not been acetolysed (Riddick et al., 2016). Several factors make them useful bio-indicators in paleoenvironmental studies (Komarek and Jankovska, 2001), including:

1. resistance to chemical treatment through the preparation of pollen slides;
2. abundance in freshwater lakes and ponds;
3. cosmopolitan distribution.
4. limited ecological tolerances and preferences of individual taxa

Green algae have been used to reconstruct salinity, temperature, pH and available nutrients for aquatic environments (Jankovska and Komarek, 2000; van Geel, 2001). A frequently reported green algae is the genus *Pediastrum* (Division Chlorophyta; Class Chlorophyceae; Order Chlorococales; Family Hydrodictyaceae) that is easily identifiable in pollen slides. Many studies that do not identify *Pediastrum* down to species level (e.g. Danesh et al., 2013; Cook et al., 2011; Yu, 2000; Hu et al., 1995; Burden et al., 1986) as the total concentrations of this genus alone is typically indicative of responses to increased nutrient levels (Jankovska and Komarek, 2000; Komarek and Jankovska, 2001; Batten, 1996) due to natural and anthropogenic changes. However, Jankovska and Komarek (2000) and Volik et al. (2016) suggest that determining species or subspecies level can be crucial at times during paleoecological reconstructions, as not all species respond the same to changes in climate. Some recent studies have shown that specific *Pediastrum* species are sensitive to pH (Weckstrom et al., 2010; Turner, 2012), availability of nutrients (Bradshaw et al., 2005; Komarek and Jankovska, 2001) and water quality (Danesh et al., 2013). Although many studies have shown how *Pediastrum* can be used for paleoenvironmental reconstruction, Whitney and Mayle (2012) conclude that the effects of climate change could be the most important control on *Pediastrum* assemblages.

Other acid-resistant coccal green algae such as *Cosmarium spp.*, *Euastrum spp.*, and *Botyococcus spp.*, can also be used as paleoenvironmental indicators. *Botryoccoccus spp.* have been reported as having specific responses to climatic conditions and the trophic state of lakes by Jankovska and Komarek (2000), Batten and Grenfell (1996), Guy-Ohlson (1992), and Komarek and Marvan (1992). Unfortunately, more research is needed specifically on *Botryococcus sp.*, as their taxonomy and paleoecology still remains somewhat unclear (Komarek and Marvan, 1992). The genus *Cosmarium spp.* has been found to have specific ecological preferences when determined down to the species level. Stastny (2009) described *Cosmarium pseudopyramidatum* as being favourable to oligomesotrophic conditions, along with *C. pyramidatum*. It was also noted that *Euastrum ansatum* could be found throughout lakes with mesotrophic conditions.

It is not only the number or presence of individual taxa that can determine specific ecological conditions, but also species diversity. Stastny (2009) determined that trophic conditions could play an important role in the number of species as well as the pH of lakes in the Czech Republic. Oligotrophic lakes tend to be the most acidic, followed by mesotrophic, and eutrophic were found to be mostly neutral or slightly basic in nature. The mesotrophic lakes had the largest number of total taxa found (90), eutrophic lakes were recorded to have much less (30), but still a reasonable number of taxa and oligomesotrophic lakes had only between 20 and 30 taxa. Overall, as the species richness increased across certain lake trophic levels, the number of each individual taxon consistently decreased.

NPPs alone can be used as bio-indicators for paleoenvironmental reconstruction, but coupled with results from the LOI method and ITRAX X-ray fluorescence core scanning system, more information can be determined about the impacts of dust loading on aquatic ecosystems.

Through analysis of the current literature on resource development, dust impacts on vegetation and near-surface permafrost temperature regimes and the changing climate, it is clear that more information needs to be present on the impacts of dust loading on

Arctic aquatic ecosystems. The current methodologies, such as the use of sediment cores as paleoenvironmental indicators, will be useful throughout this study, while the use of multiple forms of analysis will ensure that the impacts associated with dust deposition on aquatic ecosystems can be used in future studies.

2.6.2 The Use of ITRAX X-Ray Fluorescence Core Scanning System

The ITRAX X-ray fluorescence core scanning system is a non-destructive and quick way of determining elemental variations throughout lake sediment cores at a very fine resolution (0.05 mm). Several studies have proven that the ITRAX X-ray fluorescence core scanning system is beneficial in paleolimnology and the reconstruction of climate variability (Cuven et al., 2015; Gadd et al., 2015; Kylander et al., 2011), but according to Rubio et al. (2013) some of the work with ITRAX deals also with paleooceanographic sediments. Kylander et al. (2011) used a multi-proxy study inclusive with both diatoms and ITRAX to look at changes in lake productivity in response to abrupt climate change during the last glacial period in Western Europe. Kylander et al. (2011) found that peaks in the Mn/Ti ratio were indicative of decreases in lake productivity. They also concluded that a decrease in the Zr/Rb ratio indicated an increase in more fine-grained materials being added to the sediment record. The increase in fine-grained materials represented increases in aeolian transport, meaning that during times of low Zr/Rb ratio, aeolian transport was the main method of sediment transfer into the lakes. Cuven et al. (2015) found that changes in K^+ were related to grain size. Increased K^+ in their analyses occurred in conjunction with reciprocal decreases in grain size, so changes in K^+ can suggest changes in sediment transport. Overall, these studies suggest that several climatic events were identifiable throughout the sediment core using the ITRAX method, and that this method could be used as a fast and non-destructive way to help plan what portions of a sediment core should be analysed further and at what resolution.

A study completed in Sydney, Australia also used a multi-proxy study that included geochemical and radiochemical techniques together with the ITRAX X-ray fluorescence core scanning system. The goal was to reconstruct the environmental history of a lake that had a nuclear research reactor in its catchment. Gadd et al. (2015) found that increases in Cu^{2+}, Zn^{2+} and Pb^{2+} were mostly anthropogenic in nature. This study also suggested that decreases in elements near the top of the core could be due to increases in sediment loading. Gadd et al. (2005) concluded that urban development has resulted in an increase in both sediment loads and metal concentrations across all lakes within the study catchment where anthropogenic changes had previously occurred.

The ITRAX X-ray fluorescence core scanning system can be beneficial in multi-proxy studies as it allows the determination of element concentrations throughout cores up to 1.8 m in length. Understanding the fluctuation in element concentrations throughout a lake sediment core can help determine whether impacts are anthropogenic or natural and what type of sediment transfer was occurring at specific periods in time as related to grain size information. The ITRAX X-ray fluorescence core scanning system will play a large role in the determination of the calcareous dust impacts associated with the Dempster Highway in this study by examining how certain elements change over time.

Chapter 3

Site Description and Methodology

3.1 Introduction

Lake sediment cores and water chemistry measurements were collected from a suite of lakes located between Fort McPherson, NWT and the Yukon border along the Dempster Highway during two consecutive spring/summer seasons. This chapter will describe the location, the physical characteristics and the methods used to collect and analyze the data.

3.2 The Peel Plateau

3.2.1 Location

The Peel Plateau is located in the northwest portion of the Northwest Territories and continues west into the Yukon Territory, covering an area of ~59,970 km^2 (Yukon Ecoregions Working Group, 2004) (Figure 3.1). It lies between the Mackenzie Mountains (to the south) and the Richardson Mountains (to the west), with a general elevation between 100 m and 650 m above sea level (Catto, 1996; Hadlari, 2006). The geology of the Peel Plateau consists of moraine and glaciofluvial deposits that are underlain by Cretaceous sandstones (Norris, 1984; Norris and Hopkins, 1977; Yorath and Cook, 1981), which are underlain by a succession of Devonian, Carboniferous (~1,900 m thick), and Proterozoic sedimentary rocks (Hadlari, 2006; Yukon Ecoregions Working Group 2004; Yukon Geological Survey, 2015).

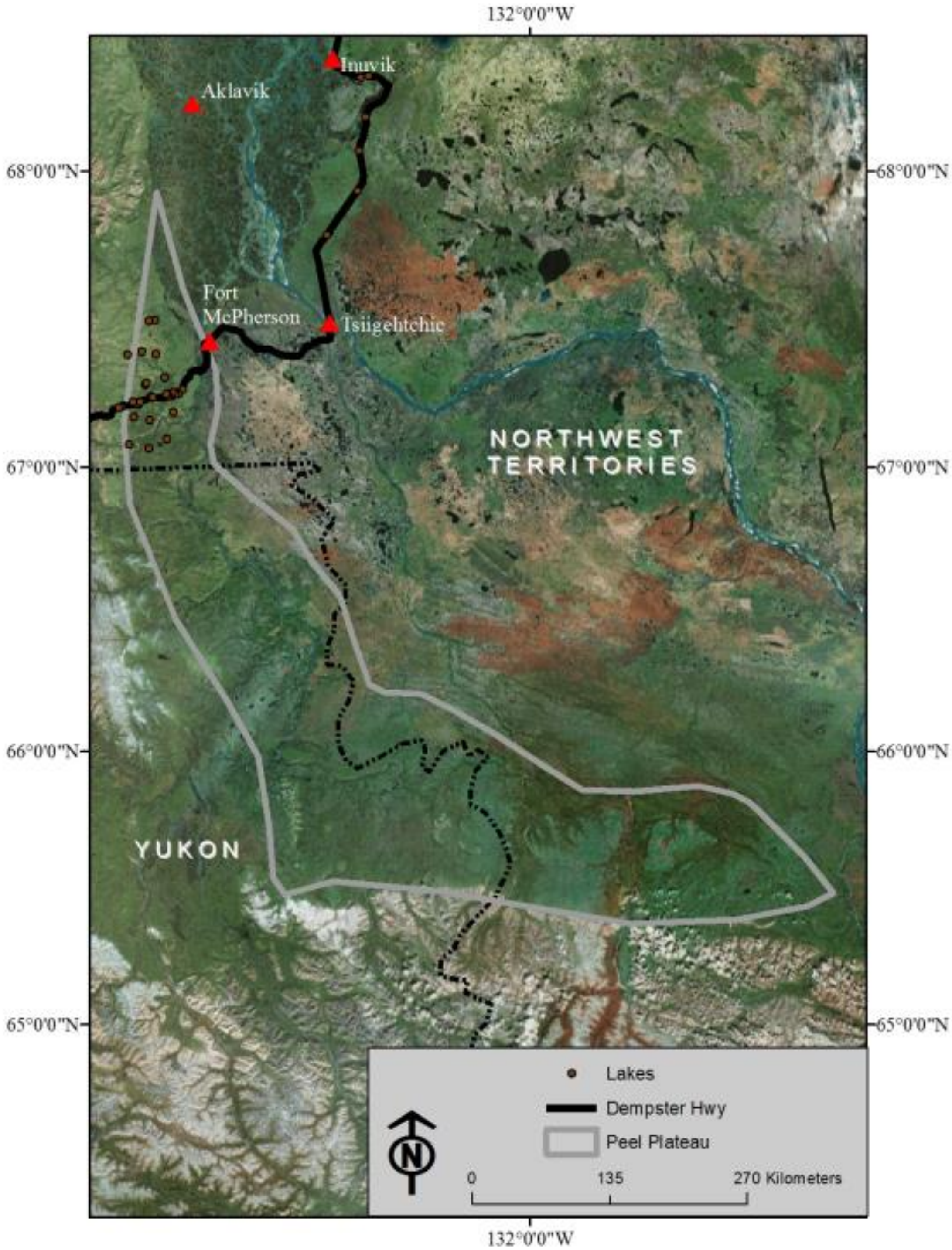

Figure 3.1 The location of the Peel Plateau is shown outlined in grey. The Dempster Highway is shown with a thick black line and the study lakes with dark red circles.

3.2.2 Surficial Geology

During the Wisconsinian glaciation, the Peel Plateau was largely covered by the Laurentide Ice Sheet (Fulton, 1995), which reached its maximum in this region at approximately 30,000 BP (Murton, 2009). The surficial deposits in this area are therefore mostly glacial in origin, consisting of glaciofluvial, glaciolacustrine and morainal sediments (Yukon Ecoregions Working Group, 2004). Dixon et al. (1992) described these sediments as mixed, fine-grained and ice-rich. The remaining deposits comprise both postglacial colluvium and alluvium (Duk-Rodkin and Hughes, 1992a,b; National Energy Board, 2000). Colluvium deposits are present along the foothills, valley sides and can be sporadic with exposed bedrock in between, while alluvium deposits are found along streambeds (Yukon Ecoregions Working Group, 2004).

Sedimentary rocks are dominant throughout the Peel Plateau landscape and can release generous amounts of carbonates into surrounding lakes. Within the last 40 years there have been consistent increases in Ca^{2+}, Mg^{2+}, and SO_4^{2-} in lakes within the Peel watershed due to the dominant sedimentary landscape (Stantec, 2012). Increases in these ions suggest previously unexposed sedimentary rocks have become weathered with the changing climate and therefore have been more susceptible to runoff or large flow events (Stantec, 2012). This is important to note, as these water chemistry variables are a key component of this study.

3.2.3 Climate

The Peel Plateau is within the boundaries of the high sub-arctic climate zone, experiencing long, cold winters and short, cool summers. This area is relatively dry due to the orographic effect of the Ogilive Mountains to the south that block moisture brought by Pacific systems (Klock et al., 2001). At Fort McPherson, the 30-year climate normal (1981-2010) shows an average annual temperature of -7.3°C, although strong winter temperature inversions cause annual temperatures on the Peel Plateau to be higher than areas near Fort McPherson (O'Niell et al., 2015b). Mean annual precipitation is 297.9 mm (1981-2010) (Figure 3.2) (Environment and Natural Resources Canada, 2016).

The winds in the Peel Plateau area have not been extensively studied, but data gathered between 1981 and 2010 at the Fort McPherson A station (43.28 m a.s.l.) from Environment and Natural Resources Canada (2016c) shows a predominant direction of wind gusts from the north and at times from the west (Table 3.1). Environment and Natural Resources Canada (2016c) does not have monthly data for the Fort McPherson station, but it does at Inuvik Station A, ~143 km east of the study lakes. Winds in and around the Peel Plateau can be dependent on the height of the station above sea level. Pinard et al. (2015) concluded that wind speeds and directions varied slightly between an area that was 240 m a.s.l., and one that was 300 m a.s.l. Since Inuvik A is 67 m a.s.l., and Fort McPherson A is only 43 m a.s.l., it is likely that the wind speed and direction at Fort McPherson are slightly different, but the Inuvik A station is the closest location to the study lakes that contains data. Between 1981 and 2010 the predominant wind direction at Inuvik A was from the east.

The cold season is typically from October (when freeze up occurs) to May. The cold season in the Peel Plateau is generally dry with the heaviest snowfall occurring in the fall and early winter months (Klock et al., 2001). More than half of the total precipitation falls as snow, with the largest amount falling in October (37.6 cm). The

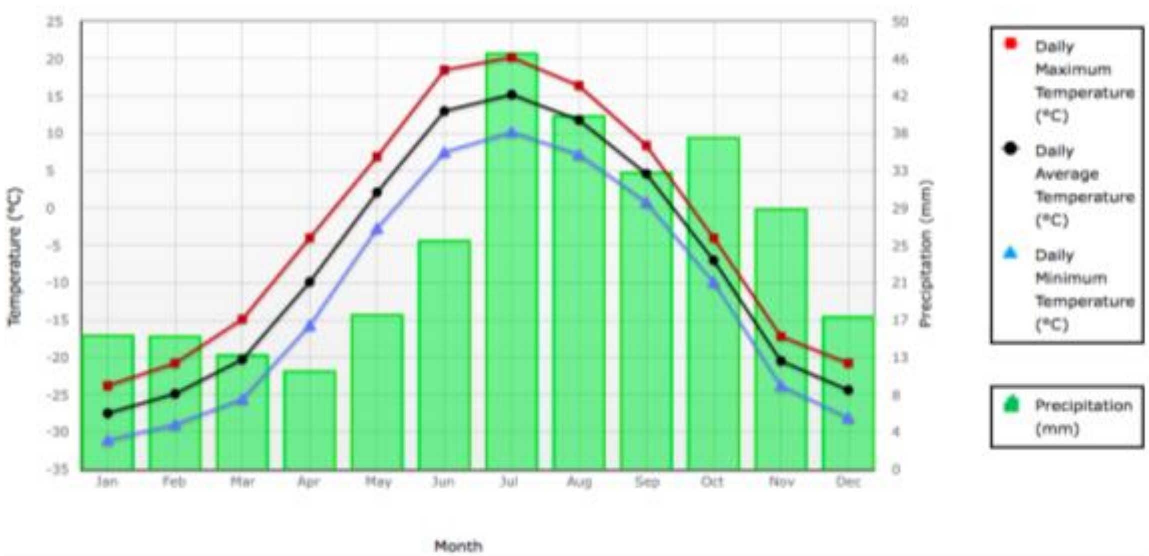

Figure 3.2 Daily maximum, average and minimum temperature and mean monthly precipitation (1981-2010), Fort McPherson A meteorological station (Environment and Natural Resources Canada, 2016).

Table 3.1 Measured maximum hourly wind speeds (m/s) and their direction from 1981 to 2010 in Fort McPherson (43 m a.s.l.). The wind direction is mostly from the north, but at times can be more westerly. Values adapted from Environment and Natural Resources Canada (2016).

Climate Normals 1981-2010

Winds at Station: Fort McPherson A

Latitude: 67°24'28.000" N

Longitude: 134°51'37.000" W

Elevation: 43 m a.s.l.

Maximum Hourly Wind Speed (m/s)	Date (yyyy-dd)	Direction of Maximum Hourly Wind Speed
10.23	2009-13	North
10.28	2008-15	West
10.28	2004-30	North
14.40	2004-01	North
9.17	2003-30	North
10.28	2003-01	North
9.17	2001-01	North
12.78	1992-01	North
15.56	1990-16	West
10.28	1990-01	West
12.78	1990-01	North
11.39	1989-01	West

coldest month is January with a daily average temperature of -27.7°C (1981-2010) (Environment and Natural Resources Canada, 2016).

The warm season is generally from June through August. Temperatures can be relatively warm, partially due to the increasing daylight hours during this time (Dyke, 2000). July is often the warmest, with a daily average temperature of 15.2°C (1981-2010) (Figure 3.2). Daily maximum temperatures generally do not exceed 20°C. The precipitation during the warm season is mostly in the form of rain and makes up approximately one half of the precipitation for the entire year, with the highest amount falling in July (46.4 mm) (1981-2010) (Environment and Natural Resources Canada, 2016).

3.2.4 Hydrology

The Peel River is a sub-watershed of the much larger Mackenzie River Basin (Figure 3.3) (Northwest Territories Water Stewardship, 2011; Canadian Parks and Wilderness Society (CPAWS) - Yukon, 2016). The Peel Watershed covers an area of 68,000 km^2 and includes six rivers (Ogilvie, Blackstone, Hart, Wind, Snake and Bonnet Plume) flowing from the Yukon into the Peel River, which travels through the Mackenzie River Delta and onto the Arctic Ocean (Beaufort Sea) (CPAWS – Yukon, 2016; The Peel Project, 2016). Along with the six major tributaries to the Peel River, there are numerous smaller rivers that drain the Richardson Mountains such as the Caribou, Trail, Road and Vittrekwa Rivers, which flow directly into the Peel River (Kenyon and Whitley, 2008).

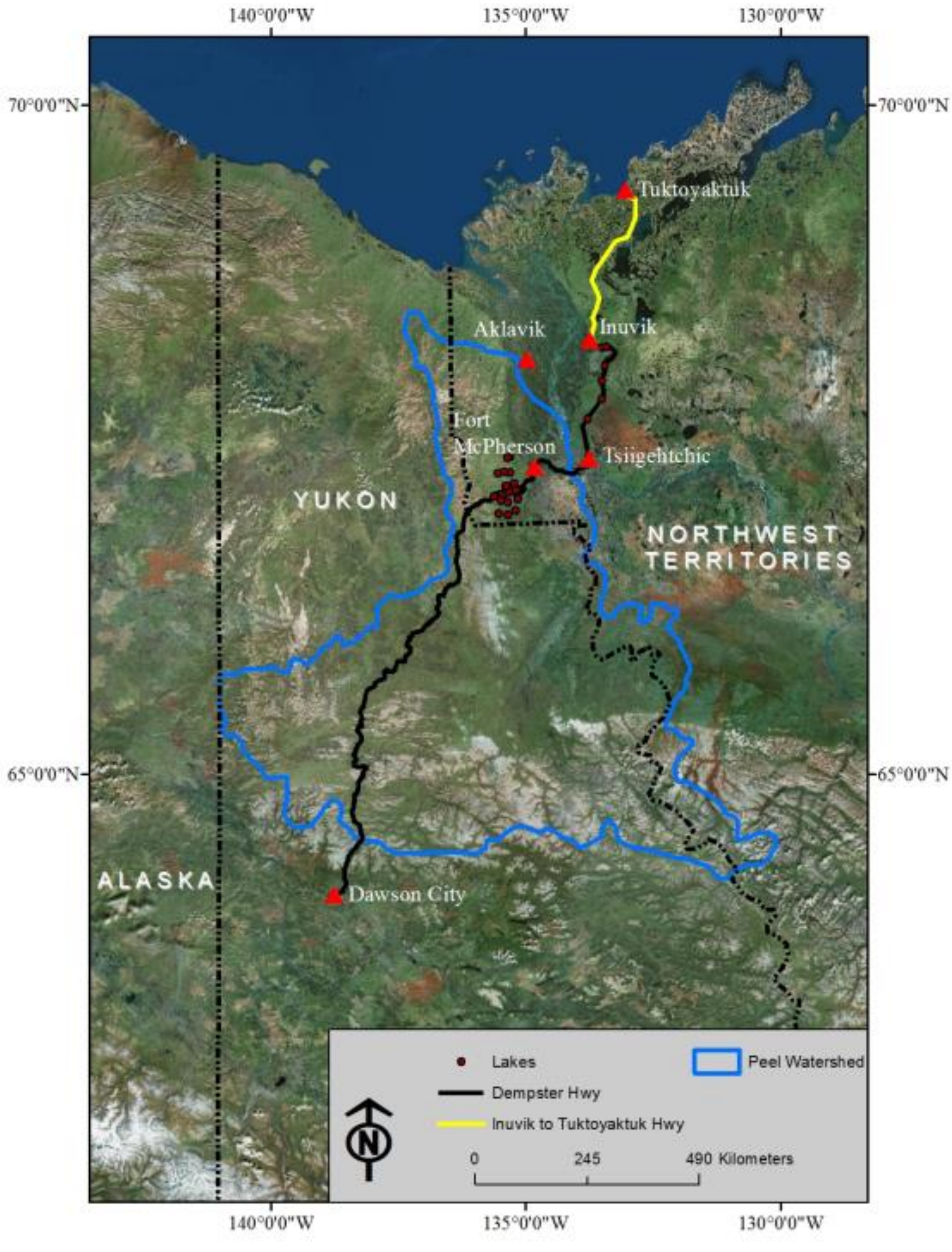

Figure 3.3 The extent of the Peel River watershed is outlined in blue and the suite of study lakes are portrayed by dark red circles. The original Dempster Highway, finished in 1979, is shown in black, and the addition of the Inuvik to Tuktoyaktuk Highway (ITH) is shown in yellow.

Wetlands in the Fort McPherson Plain and along the Peel Plateau ecoregions are very similar in both type and abundance. Wetlands occur throughout the Canadian Arctic but are most seldom in the middle and higher Arctic areas, such as the Peel Plateau (National Wetlands Working Group, 1986). The wetlands in the middle and high Arctic are covered by mosses and sedges and mostly occur on depressions or slopes. The reason for the occurrence of wetlands along depressions or slopes is that there are perennial or late-thawing snow beds that act as a constant water supply (Tarnocai and Zoltai, 1988).

The Peel River Watershed is dotted with many small lakes and ponds. There is a scarcity of wetlands and large amounts of permafrost throughout the area, meaning there are limited amounts of melt water that can be stored within the watershed area. As expected, the peak annual streamflow occurs a few weeks following the annual snowmelt (late May to early June). This peak flow has the potential to be exceeded by large summer rain events, but this is mostly dependent on the stream size, as a smaller stream will reach a peak flow much faster than a larger stream (Stantec, 2012).

At this time, there is controversy about development within the Peel River watershed. Until approximately 2004, there had been no interest in developing the area surrounding the Peel River, but that has since changed. The Yukon Government has tried to open up approximately 70% of the Peel River Watershed to industrial development practices such as mining and fossil fuel extraction. The fight to keep the Peel River watershed undeveloped has continued as far at the Supreme Court of Canada as of June 9th, 2016 (CPAWS – Yukon, 2016).

3.2.5 Vegetation

The Peel Plateau is overlain with fine-textured and poorly drained tills that are favourable for black spruce (*Picea mariana)* that dominate the forests. Larch (*Larix laricina)*, willow (*Salix spp.)*, mountain cranberry (*Vaccinium vitis-ideaa)*, cloudberry *(Rubus chamaemorus)*, labrador tea *(Rhododendron tomentosum) (syn Ledum palustre)*, bearberry (*Arctostaphylos uva-ursi)*, and lichen also favour the till conditions within the Peel Plateau. On alluvial platforms that are more effectively drained, such as slopes and along major rivers or streams, white spruce (*Picea glauca)* is dominant, with lesser amounts of mountain alder (*Alnus viridis subsp. cripsa) (A. crispa*), horsetail (*Equisetum spp.)*, and mosses (Smith et al., 2004). At the higher elevations shrubs such as: alpine blueberry (*Vaccinium uliginosum)*, mountain cranberry, dwarf birch (*Betula nana)*, labrador tea, dominate on hummocky terrain, in association with cloudberry, sedges (Cyperaceae), mosses, and lichens (Stanek et al., 1981).

3.3 The Dempster Highway

The Dempster Highway is a 740 km all-weather gravel highway that runs through both the Ogilvie and Richardson mountain ranges. It begins in Dawson City, Yukon where it soon crosses the continental divide three times, traverses the Arctic Circle and ends in Inuvik, Northwest Territories (Figure 3.4) (Dempster Highway, 2016; The Peel River Inn, 2016; Yukon Info, 2016). Within the first 40 km from Dawson City, the Dempster Highway crosses three different ecoregions: the Klondike Plateau, Yukon Plateau and the North Mackenzie Mountains (Northwest Territories and Yukon, 2014).

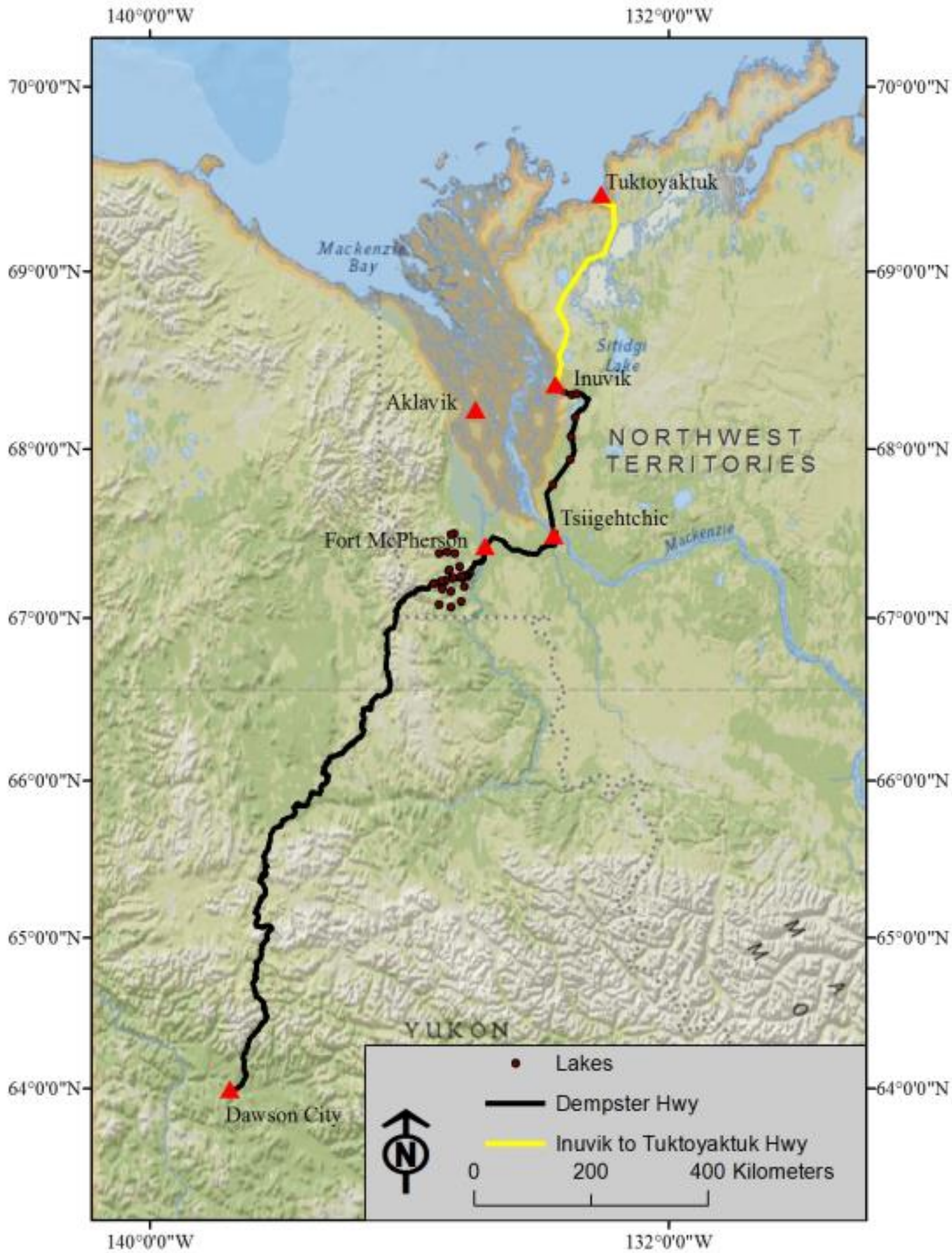

Figure 3.4 The Dempster Highway from Dawson City, Yukon to Inuvik, Northwest Territories is shown in black and the addition of the Inuvik to Tuktoyaktuk Highway (ITH) that is projected to open in the fall of 2017 is shown in yellow. The study lakes are shown as dark red circles.

Once the Dempster Highway traverses into the Northwest Territories, it crosses both the Peel River and the Mackenzie River. As the highway must cross these rivers, beginning at the Peel River there is warm season access by ferries, and cold season access by ice roads. There is a three to four week timeframe when the Dempster Highway is not accessible north of the Peel River due to spring breakup and the fall freeze-up (Dempster Highway, 2016). Once in the Northwest Territories and north of the Peel River, the Dempster Highway crosses three other ecoregions: the Peel River Plateau, Fort McPherson Plain and the Arctic Red Plain, leading to the Mackenzie Delta and to the final destination, the town of Inuvik (Northwest Territories and Yukon, 2014).

The speed limit along the Dempster Highway is 90 km/h and calcium chloride is used on the road in certain areas to create dust-free passing zones. Service areas can be found along the Dempster Highway at Eagle Plains (370 km from Dawson City), at Fort McPherson (550 km from Dawson City) and then at Inuvik (736 km from Dawson City). There are also other services such as campgrounds, airports, washrooms, gas stations, and lookouts, along the route (The Peel River Inn, 2016; Yukon Info, 2016).

Construction of the Dempster Highway began originally in 1959 (Yukon Info, 2016) due to the fact that the oil and gas industry (mostly exploration) was growing rapidly, and the town of Inuvik was currently under construction (Dempster Highway, 2016). Unfortunately, there was a lot of hostility between the Yukon and federal governments, which caused the Dempster Highway to be built very slowly. Not long after construction began, it was halted and the project was temporarily abandoned in 1961. Finally, in 1968 construction resumed because the Canadian government wanted sovereignty over the Arctic seabed in the Beaufort Sea and over the Arctic islands that had yet to be formally claimed by any nation (Dempster Highway, 2016). Construction was completed and the Dempster Highway opened officially on August 18th, 1979 (Northwest Territories and Yukon, 2014; Yukon Info, 2016).

3.4 Site Description

The study site is located in the northwest portion of the Northwest Territories, Canada (Figure 3.5) and includes a suite of 28 lakes that extend across the Dempster Highway between the town of Fort McPherson and the Yukon border. The 28 lakes being examined in this thesis run along 25 km of the Dempster Highway from east to west and 48 km from the north to the south side of the highway. Out of the 28 lakes, 25 of them had water chemistry taken in the 2014 and 2015 field seasons, while the other three lakes had both lake sediment cores and water chemistry taken during the 2014 and 2015 field seasons. The lakes were picked based upon their distance from the highway to gain an understanding of how the water chemistry and elemental profiles change between lakes within a close proximity to the highway and those that are farther away. Table 3.2 shows the exact location and the distance from the Dempster Highway for each of the 28 lakes.

The three lakes that are of focus throughout this thesis will be known informally as FM02, FM04 and FM06 (Figure 3.5), in order from closest to the Dempster Highway to farthest away. Both FM02 (~50 m) and FM04 (~670 m) are considered to be impacted lakes, based on their distance away from the highway, and FM06 (~23 km) is the control lake for this study.

Table 3.2 All 28 lakes in order of their distance from the Dempster Highway, including both their name and their exact location (taken from the middle of each lake).

Lake Name	Distance (km)	Latitude and Longitude	Lake Size (ha)	Direction From Highway	Depth (m)
FM03*	0.04	67 15'30.6" N 135 6'48.26" W	1.7	North	2.0
FM02	0.05	67 14'30.49" N 135 19'34.77" W	2.0	North	2.0
FM10	0.05	67 16'8.25" N 135 3'52.26" W	4.5	South	1.5
FM50	0.06	67°15'7.94" N 135° 7'46.27" W	0.23	South	1.0
FM17	0.21	67 12'30.68" N 135 37'29.78" W	0.33	North	1.8
FM11	0.24	67 14'38.95" N 135 11'16.89" W	1.1	South	1.0
FM12	0.43	67 13'3.62" N 135 27'21.25" W	2.0	South	0.8
FM05	0.43	67 14'39.00" N 135 20'23.29" W	1.7	North	1.5
FM14*	0.57	67 15'12.99" N 135 11'36.09" W	6.8	North	2.0
DEMPLK 1*	0.64	67 15'9.46" N 135 12'5.04" W	2.6	North	4.0
FM04	0.67	67 15'7.06" N 135 5'57.31" W	1.5	South	3.0
FM15	0.73	67 13'31.86" N 135 30'10.79" W	0.64	North	1.0
DEMPLK 2*	0.79	67 15'9.55" N 135 12'25.72" W	0.73	North	7.0
FM16	0.93	67 15'26.20" N 135 9'15.79" W	1.7	North	4.0
FM18	0.95	67 13'25.30" N 135 34'57.88" W	5.9	South	3.5
FM19	4.82	67 10'30.79" N 135 29'35.36" W	3.9	South	3.7
DEMPLK 3	5.48	67 17'5.09" N 135 24'0.64" W	8.6	North	2.6
FM20	5.77	67 11'32.88" N 135 8'56.10" W	5.3	South	1.7
DEMPLK 4	5.86	67 17'25.85" N 135 22'53.96" W	1.9	North	4.5
FM27	7.66	67 18'32.22" N 135 13'39.74" W	3.2	North	3.9
FM21	8.12	67 9'48.76" N 135 21'21.04" W	1.7	South	2.6
FM23	15.68	67 5'57.17" N 135 12'2.85" W	8.3	South	>7.0
FM30	16.72	67 23'21.50" N 135 18'14.30" W	3.1	North	1.8
FM29*	18.47	67 23'53.18" N 135 25'32.69" W	9.0	North	6.0
FM28	18.92	67 23'11.17" N 135 32'56.08" W	1.9	North	3.0
FM24	18.93	67 4'3.98" N 135 21'41.66" W	0.90	South	3.5
FM06	23.62	67 30'20.23" N 135 18'35.33" W	0.91	North	3.5
FM31	29.87	67 30'4.01" N 135 21'59.31" W	4.0	North	6.5

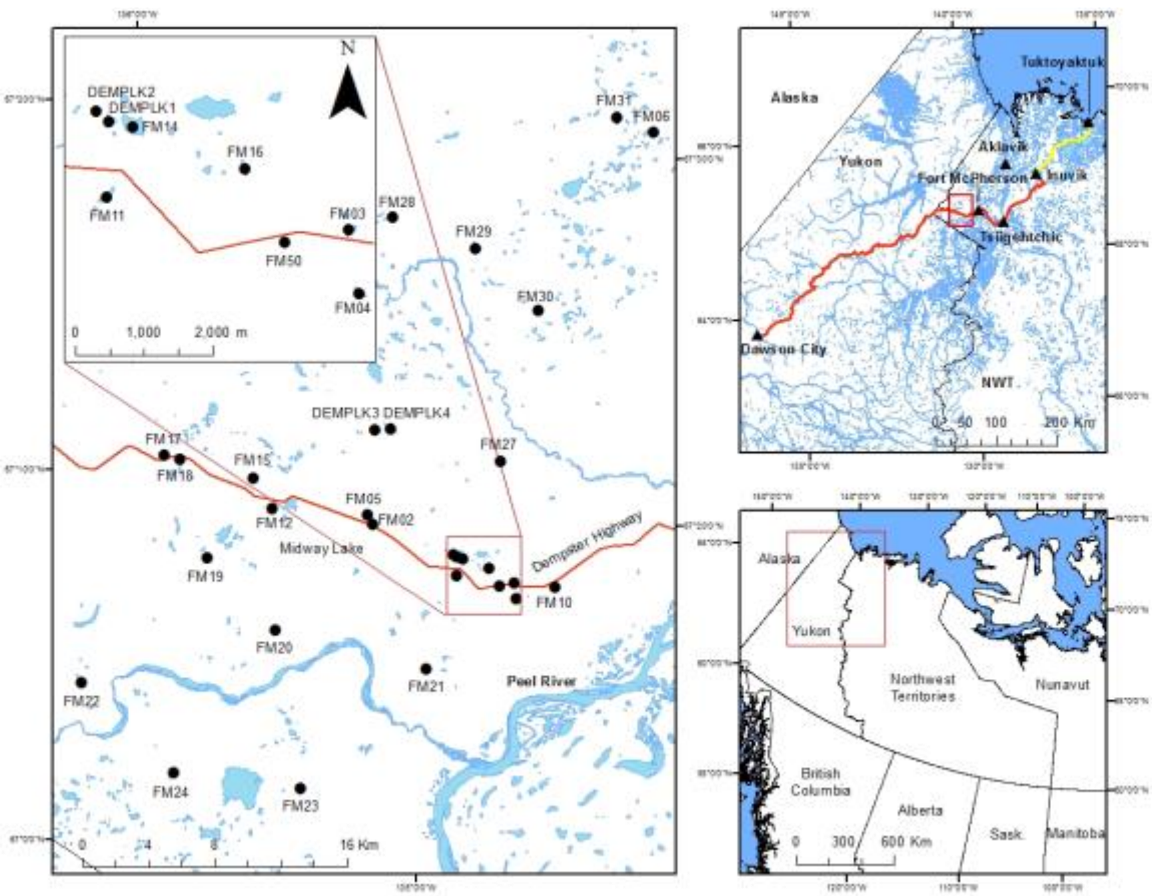

Figure 3.5 The study area shows the location of all 28 lakes (circles, far left) in relation to the Dempster Highway (in red). Black triangles in the top right map show the location of various towns surrounding the study lakes, including Dawson City, Tsiigehtchic, Fort McPherson, Aklavik, Inuvik and Tuktoyaktuk.

Lake FM02 is located approximately 50 m north of the Dempster Highway and is surrounded by graminoids, mosses and both short and tall shrubs (Figure 3.6). This lake has a surface area of 2.0 ha and is a shallow lake, only 2.15 m deep. During the two field seasons, the ice on lake FM02 averaged 1.2 m in thickness. FM02 is one of the closest lakes to the Dempster Highway, and would be considered upwind since the predominant wind directions are north and west. Lake FM02 is considered one of the impacted lakes throughout this thesis.

Lake FM04 is located approximately 670 m south of the Dempster Highway and has similar vegetation cover to FM02, but does have some stunted stands that include black spruce, white spruce, mountain alder, dwarf birch and willow (Figure 3.7). FM04 has a similar surface area to lake FM02 (approximately 1.5 ha). The depth of lake FM04 was measured at 2.95 m and ice thickness was ~1.3 m on average between the 2014 and 2015 field seasons. FM04 was chosen as the second impacted site in order to determine if the dust from the Dempster Highway is having any impact on the elemental variations in the lake over time and to determine if wind patterns may have an influence on how the dust is distributed. Although FM02 and FM04 are similar in terms of surface area and depth, FM04 is approximately 620 m farther away from the Dempster Highway and is downwind when compared to FM02. The two lakes are located on opposite sides of the Dempster Highway.

Lake FM06 is the control lake for this study, located 24 km to the north of the Dempster Highway (Figure 3.8). FM06 is slightly smaller and shallower than the impacted lakes (FM02 and FM04): surface area of 0.91 ha and ~3.5 m deep.

Figure 3.6 Oblique photograph of lake FM02 from the helicopter (courtesy of Dr. Michael Pisaric). This picture was taken looking north, as the Dempster Highway is visible at the bottom of the image. FM02 is approximately 50 m north of the highway corridor and it is expected to receive inputs of road dust.

Figure 3.7 Oblique photograph of lake FM04 from the helicopter (courtesy of Dr. Michael Pisaric). This picture was taken looking south, with the Dempster Highway to the north. The Dempster Highway is not visible in this photo as FM04 is approximately 700 m south of the highway.

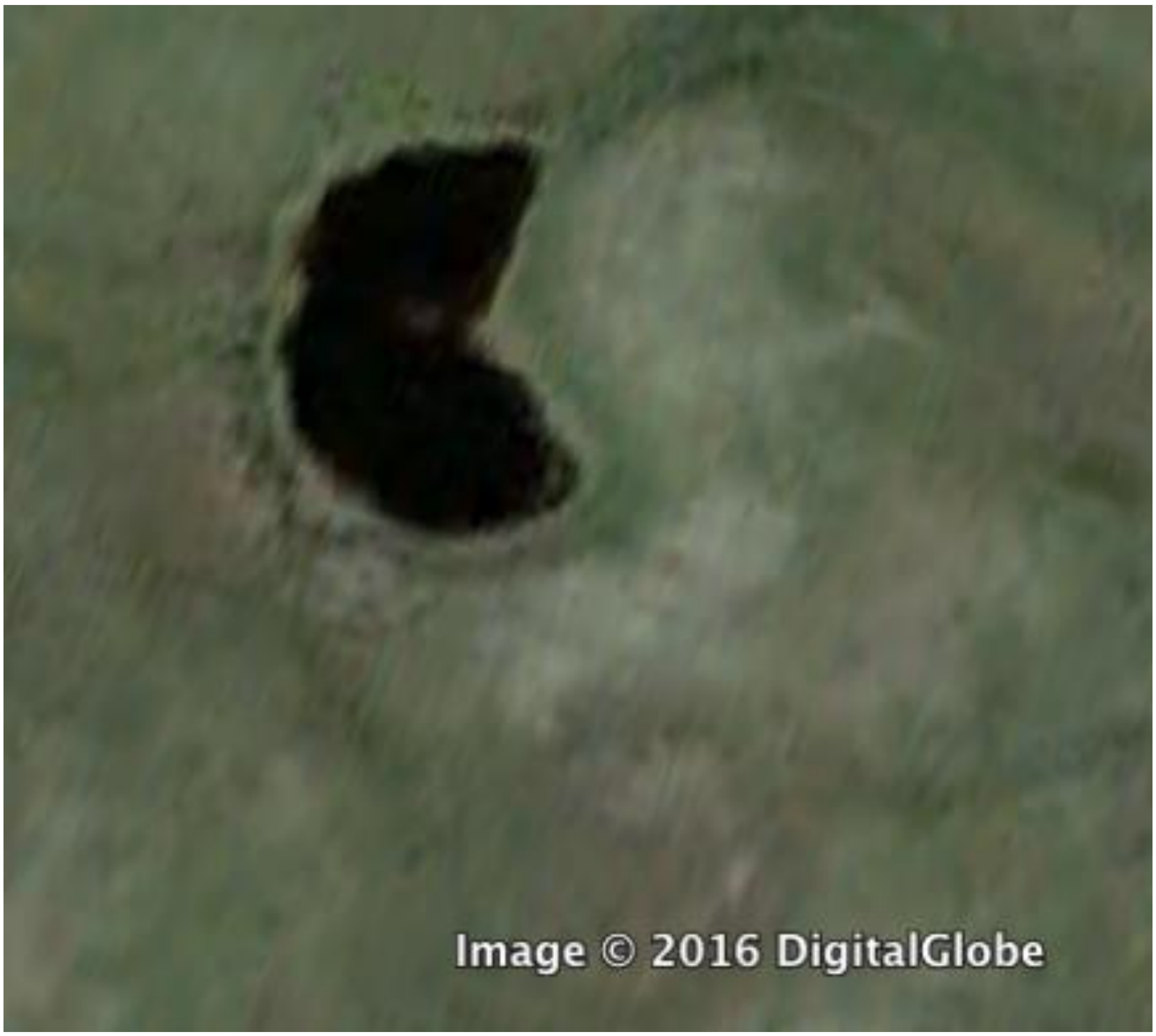

Figure 3.8 Lake FM06 (the control) from Google Earth. The darker green areas of this photo are the stunted stands of black spruce, white spruce, dwarf birch, willow and mountain alder, as well as other coniferous trees. (Google Earth, 2015).

Average ice cover for FM06 was measured between the 2014 and 2015 field seasons as 0.78 m. Similar to FM04, the control lake is surrounded mostly by mosses, graminoids and short to tall shrubs, but does have stunted stands of black spruce, white spruce, mountain alder, dwarf birch and willow. Being almost 30 km away from the Dempster Highway, FM06 was used as the control as there is no evidence of industrial development or large anthropogenic impacts of any type.

The other 25 lakes that will be investigated throughout this thesis are of varying surface areas, directions and distances from the Dempster highway (Table 3.1). The goal was to choose approximately one third of the lakes between 0 km and 5 km, one third to be between 5 km and 20 km and one third to be >20 km away from the Dempster Highway. They were chosen in this manner to better understand how the water chemistry varies from areas that are closer to the Dempster Highway and those that are farther away. All 25 study lakes have similar surroundings to both FM04 and FM06 in regards to vegetation and geology.

3.5 Field Methodologies

Fieldwork for this study was carried out during early April 2014 (when there was still ice cover on the lakes), early May 2015 (lakes were still ice-covered), and early August in both 2014 and 2015 (warm season). Lakes FM02, FM04 and FM06 were visited in early April 2014 and May 2015 to collect sediment cores, using the ice as the coring platform. All 28 lakes were then visited in August of 2014 and 2015 to collect water samples for analysis of water chemistry.

3.5.1 Water Chemistry Collection

Water samples were collected and tested for routine water chemistry, nutrients, major ions and some trace metals from all 28 lakes along the Dempster Highway (Appendix I). The sampling method employed was courtesy of Taiga Environmental Laboratories (Table 3.3). A helicopter was used to get to the suite of lakes, as they were not all easily accessible. The helicopter was equipped with floats and landed in the middle of each lake. At each lake, one bottle (500 mL) used to determine routine water chemistry (pH, conductivity, alkalinity, Cl^-, SO_4^{2-}, F^-, NO_2-N, NO_3-N, NO_3/NO_2-N, Ca^{2+}, Mg^{2+}, K^+, hardness, reactive silica and colour) and nutrients (COD, TN, DN, turbidity, TSS, TDS, NH_3, TP, TOC, DOC, and T.Cl) was rinsed three times and then completely filled. One bottle (100 mL) used to determine total dissolved metals (Al^{3+}, Sb^{3+}, As^{3+}, Ba^{2+}, Be^{2+}, Cd^{2+}, Cs^+, Cr^{3+}, Co^{2+}, Cu^{2+}, Fe^{2+}, Pb^{2+}, Li^+, Mn^{2+}, Mo^{6+}, Ni^{2+}, Rb^+, Se^{2+}, Ag^+, Sr^{2+}, Tl^+, Ti^{3+}, U^{4+}, V^{3+}, and Zn^{2+}) was rinsed three times, filled almost to the top, 5 mL of 1:3 nitric acid was then added and the bottle was capped and mixed. The labelled bottles were placed in a refrigerator directly after arriving back to the Aurora Research Institute (ARI) and stored at 4^{o}C. Once the sampling was completed, the bottles were placed in coolers and shipped to Taiga Environmental Laboratory in Yellowknife where they were analysed for the above mentioned water chemistry parameters.

3.5.2 Lake Sediment Core Collection

Lake sediment cores were collected from lakes FM02 (impacted), FM04 (impacted) and FM06 (control) using a Uwitec gravity coring system with an internal core diameter of ~86mm (Figure 3.9). The cores were retrieved from the middle of each

Table 3.3 An outline of the sampling procedure that was used for water chemistry from Taiga Environmental Laboratory effective 2016.

PARAMETER	INSTRUCTIONS
ROUTINE	
pH, conductivity, alkalinity Individual anions: Cl^-, SO_4^{2-}, F^-, NO_2-N, NO_3-N Total nitrite and nitrate: $NO_2 + NO_3$-N Individual cations: Ca^{2+}, Mg^{2+}, K^+ Hardness (Calculated) Reactive silica (SiO_2) Color (Apparent and True)	Rinse bottle (3) times with sample Fill to top and cap the sample Keep cool at 4°C
NUTRIENTS	
Chemical Oxygen Demand (COD) Nitrogen: total (TN), dissolved (DN) Turbidity Total suspended solids (TSS) and Total dissolved solids (TDS) Ammonia (NH_3) Phosphorus: total (TP), dissolved (DP), ortho (OP) Carbon: total (TOC), dissolved (DOC) Chlorine: total (T.Cl), residual (R.Cl) Visible oil and grease	Rinse bottle (3) times with the sample Fill to top and cap the sample Keep cool at 4°C
TOTAL DISSOLVED METALS Al^{3+}, Sb^{3+}, As^{3+}, Ba^{2+}, Be^{2+}, Cd^{2+}, Cs^+, Cr^{3+}, Co^{2+}, Cu^{2+}, Fe^{2+}, Pb^{2+}, Li^+, Mn^{2+}, Mo^{6+}, Ni^{2+}, Rb^+, Se^{2+}, Ag^+, Sr^{2+}, Tl^+, Ti^{3+}, U^{4+}, V^{3+}, and Zn^{2+}	Rinse bottle (3) times with the sample Fill to near the top Add 5 mL of 1:3 nitric acid Cap bottle and mix

lake. The core lengths recovered were 52 cm (FM02, 2014 and 2015), 57 cm (FM04, 2014), 41 cm (FM04, 2015), 58 cm (FM06, 2014) and 47.5 cm (FM06 2015). A helicopter was used to access each of the lakes in the late cold season (April 2014, May 2015). At each lake, an ice auger was used to cut through the ice to create a large enough hole for the Uwitec gravity coring system to be deployed. The Uwitec gravity coring system operates as its name implies. It uses gravity to propel the plastic tube (up to 2 m in length) (Uwitec, 2016) through the sediment. The Uwitec coring system is a hybrid gravity-percussion coring system. Once the corer is pulled into the sediment by gravity, the corer can be further moved downward into the sediment by pulling weights on the top of the corer up and down. The corer was gently brought up when the desired length was reached and the core tube bottom was plugged using core plugs while the bottom of the core was still in the lake. The tops of the cores were sprinkled with Zorbitrol® (Tomkins et al., 2008) and then also capped.

The lake sediment cores were refrigerated at 4°C immediately after returning to ARI after each sampling day. The April 2014 cores were sub-sampled into 0.5 cm intervals up to 20 cm and then at 1.0 cm intervals for the remainder of the cores. The sub-samples were placed in Whirpak® bags and transported in cold storage back to Brock University where they were kept in the walk-in cooler at 4°C until analysis could occur.

The May 2015 cores were kept intact and shipped back to Brock University where they were placed in the walk-in cooler at 4°C. In the summer of 2015 the cores were transported to McMaster University where they were cut in half by Dr. Ed Reinhardt and scanned using the ITRAX X-ray fluorescence core scanning system. Half of each core

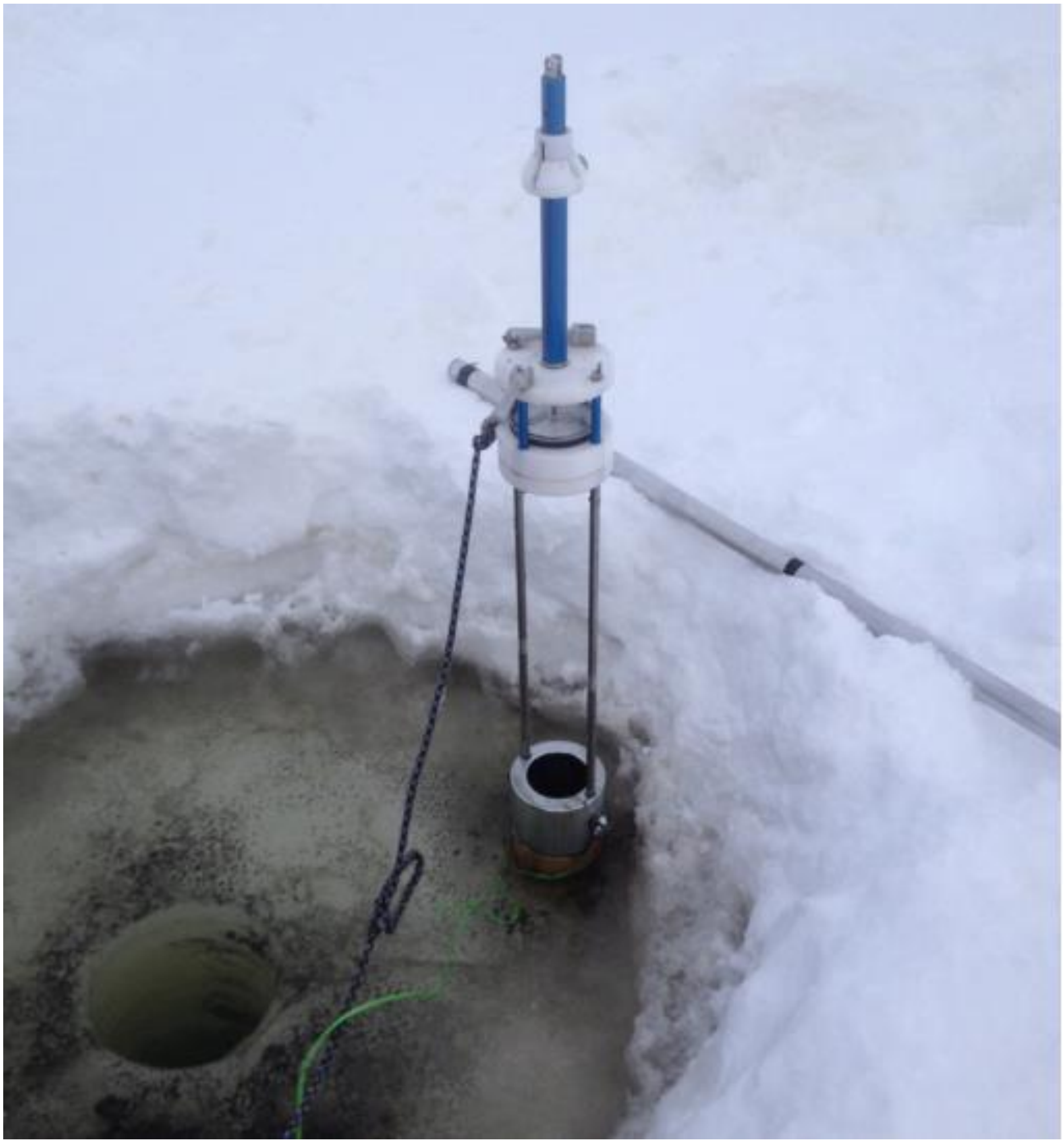

Figure 3.9 The Uwitec gravity coring system that was used to gather lake sediment cores from FM02, FM04 and FM06. Also visible in this photo to the left of the corer is one of the holes that was created using an ice auger. This is where the Uwitec gravity coring system was lowered down through the ice cover to retrieve the sediment core.

was subsampled into 1.0 cm intervals and stored in Whirlpak® bags. The sub-sampled 2015 bags were kept at 4°C in the walk-in cooler as well.

3.6 Laboratory Methods

Several laboratory methods can be employed in order to examine climatic and environmental change using the sediment record of lakes. Some of these include Loss-on-Ignition (LOI), ITRAX X-ray core scanning, and the identification of biological proxies such as non-pollen palynomorphs (NPP). These methodologies can help determine the impacts from both the climate and environment, including disturbances such as the deposition of road dust in lakes.

3.6.1 ITRAX X-Ray Fluorescence Core Scanning System

The ITRAX X-ray fluorescence core scanning system is a method that can be used to determine the changes in elemental properties of a sediment core throughout its entire profile. ITRAX provides X-ray fluorescence (XRF) profiles along with micro-radiographic images for cores up to lengths of 1.8 m, with a very fine resolution (~0.2 mm) (Croudace et al., 2006; Haschke et al., 2006; Rothwell and Rack, 2006). The ITRAX X-ray core scanning system records both physical and chemical properties throughout a lake sediment core and provides four data sets that include: (1) a high-resolution optical image (0.2 mm), (2) a high-resolution X-radiographic image (0.2 mm), (3) a measurement of magnetic susceptibility (MS) in profile form (0.2 mm) and, (4) a high-resolution scan of relative elemental variations using XRF (Zuo, 2013). The ITRAX system is widely used due to its non-destructive analysis of sediment cores and fast as compared to traditional XRF methods that utilize multiple grams of sediment for one run and is more time consuming (Croudace et al., 2006; Zuo, 2013). Although there are many advantages to using the ITRAX X-ray scanning system, Weltje and Tjallingii (2008) determined the primary disadvantage is the problematic conversion from counts per second (cps) to element concentrations (for e.g. mg/L) that are typical when using conventional geochemical analyses.

ITRAX X-ray fluorescence scanning of sediment cores is a complicated process that can be summarised in 4 steps. Sediment cores are carried by a conveyer type loading system into the ITRAX machine (Figure 3.10). Once in the ITRAX machine, X-radiation causes excitation of electrons. The excitation process leads to the ejection of electrons from their inner atomic shells, creating spaces to be filled. The electrons falling back from their outer shells then fill these voids. The surplus energy that results is then emitted as a pulse of secondary X-radiation, which is measured by the ITRAX system (Weltje and Tjallingii, 2008). The fluorescence that is emitted and the wavelength spectra will be characteristic of atoms for specific elements, therefore permitting the estimation of their abundance throughout the core.

Figure 3.10 An example of the ITRAX X-Ray fluorescence core scanning system. The core begins on the far left side where each core is aligned with the top of the core facing the right. The core moves through the middle section where the arm of the shifting Si-drift chamber detector is visible. During the analysis the split cores are moved from the left extension to the right extension. Adapted from Croudace et al. (2006).

Chapter 4

Results

4.1 Introduction

Chemical, physical and biological proxies of lake water and lake-bottom sediment were analysed to determine the response of the aquatic environment to increased dust deposition. The chemistry of water samples from a suite of 28 lakes at varying distances from the Dempster Highway in the Northwest Territories was analysed. Elemental variations through time in sediment cores from three of the study lakes (FM02, FM04 and FM06) were tracked using the ITRAX X-ray fluorescence core scanning system.

4.2 Water chemistry

In total, 48 water chemistry variables were analysed for water samples from each lake, but only 11 variables showed significant trends with increasing distance from the Dempster Highway. A t-test was used to determine whether elements in lakes within 1.0 km of the Dempster highway are significantly different than lakes more than 1.0 km away from the highway (Table 4.1). The full suite of raw water chemistry data for 2014 and 2015 can be found in Appendix I, while the raw count graphs for the 11 significant variables can be found in Appendix II.

The 11 variables that significantly decreased with distance from the highway include: alkalinity, conductivity, total dissolved solids (TDS), pH, Ca^{2+}, hardness, Mg^{2+}, nitrate (NO_3-N), nitrate/nitrite ratio (NO_3/NO_2-N), SO_4^{2-} and Sr^{2+}.

Table 4.1 The *t value*, *p-value*, and degrees of freedom are displayed for all 11 of the water chemistry variables that appeared to be significantly different between lakes that were <1 km from the Dempster Highway and those that were >1 km from the highway. The null hypothesis was that there is no significant difference within the variables between lakes <1 km from the Dempster Highway and those >1 km from the highway. The alternative hypothesis was that there is a significant difference within the variables between lakes <1 km from the Dempster Highway and those >1 km from the highway.

Variables	***t****	***p-value*****	**df**
2014			
Ca^{2+}	2.5541	0.01685	26
Hardness	2.5942	0.01537	26
Mg^{2+}	2.4618	0.02077	26
NO_3	1.0034	0.32490	26
NO_3/NO_2	1.0054	0.32400	26
SO_4^{2-}	2.0142	0.05444	26
Alkalinity	2.4340	0.02211	26
Conductivity	2.5608	0.01660	26
TDS	2.2388	0.03395	26
pH	1.1889	0.24520	26
Sr^{2+}	2.4188	0.02287	26
2015			
Ca^{2+}	2.5254	0.01799	26
Hardness	2.5582	0.01670	26
Mg^{2+}	2.4321	0.02220	26
NO_3	2.5950	0.01534	26
NO_3/NO_2	2.6016	0.01511	26
SO_4^{2-}	1.9152	0.06653	26
Alkalinity	2.8186	0.00910	26
Conductivity	2.2965	0.02996	26
TDS	2.3079	0.02922	26
pH	2.1760	0.03883	26
Sr^{2+}	2.4521	0.02123	26

* t-critical = 1.7056

** alpha = 0.05

4.2.1 Nutrients

Nutrients that were measured for all 28 lakes included ammonia (NH_3), dissolved nitrogen (DN), total nitrogen (TN), organic phosphorus (OP), dissolved phosphorus (DP), total phosphorus (TP), dissolved organic carbon (DOC) and total organic carbon (TOC). No nutrients showed a significant relationship with increasing distance from the Dempster Highway.

4.2.2 Physical Water Chemistry

The physical water chemistry variables that differed significantly with increasing distance from the Dempster Highway included: alkalinity, conductivity, total dissolved solids (TDS) and pH. T-tests on the 2014 water chemistry data determined that alkalinity, conductivity and TDS were significantly higher than in lakes <1km from the Dempster Highway than those >1 km from the highway (Table 4.1). A t-test on pH between <1 km and >1 km away from the highway showed there was no significant difference. However, in the 2015 water chemistry data, all of the above stated variables, including pH, showed a significant decrease with increasing distance from the Dempster Highway. Boxplots for these physical variables concluded that in lakes <1 km from the highway the median was higher and there was also more variability than lakes >1 km away (Figure 4.1a-d; Figure 4.2a-d).

Alkalinity, conductivity, TDS and pH all have maximum values in DEMPLK 1 (121 mg/L, 620 mg/L, 430 mg/L and 8.14, respectively). This lake is located ~640 m from the Dempster Highway and during field work it was noted there is a retrogressive thaw slump on its north side.

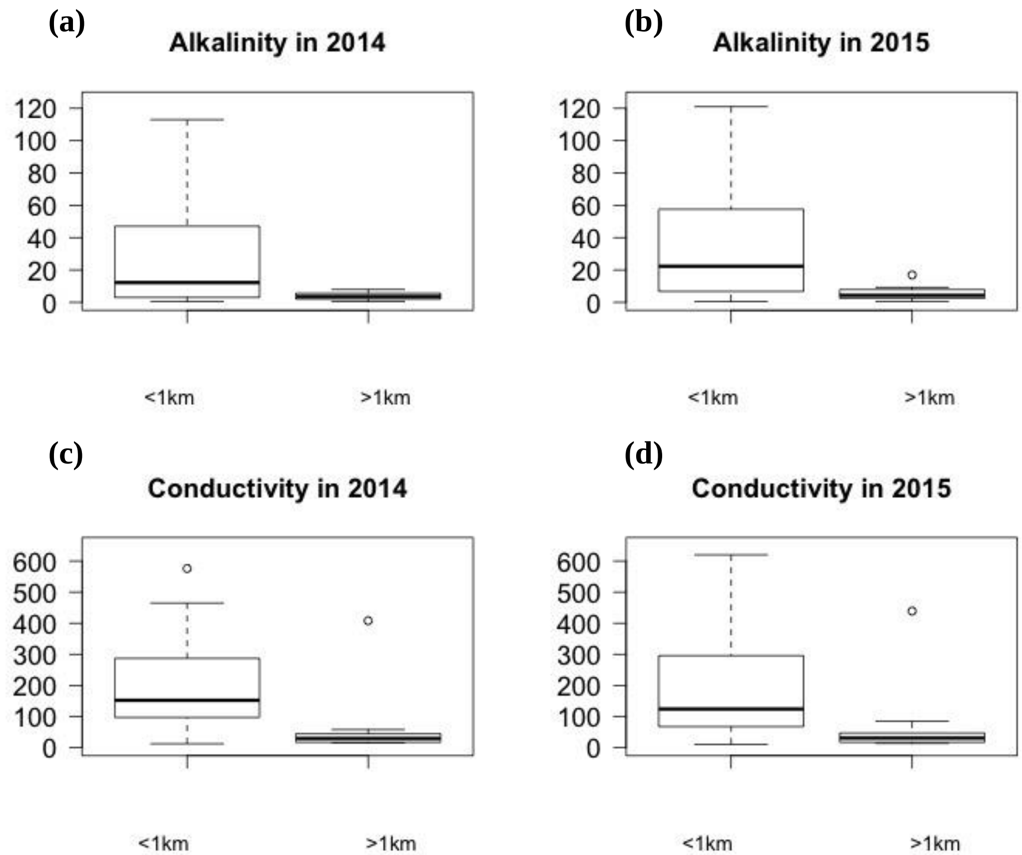

Figure 4.1 Alkalinity and conductivity boxplots are shown for years 2014 and 2015. Both alkalinity (a and b) and conductivity (c and d) show more variation and higher medians in lakes <1 km from the Dempster Highway.

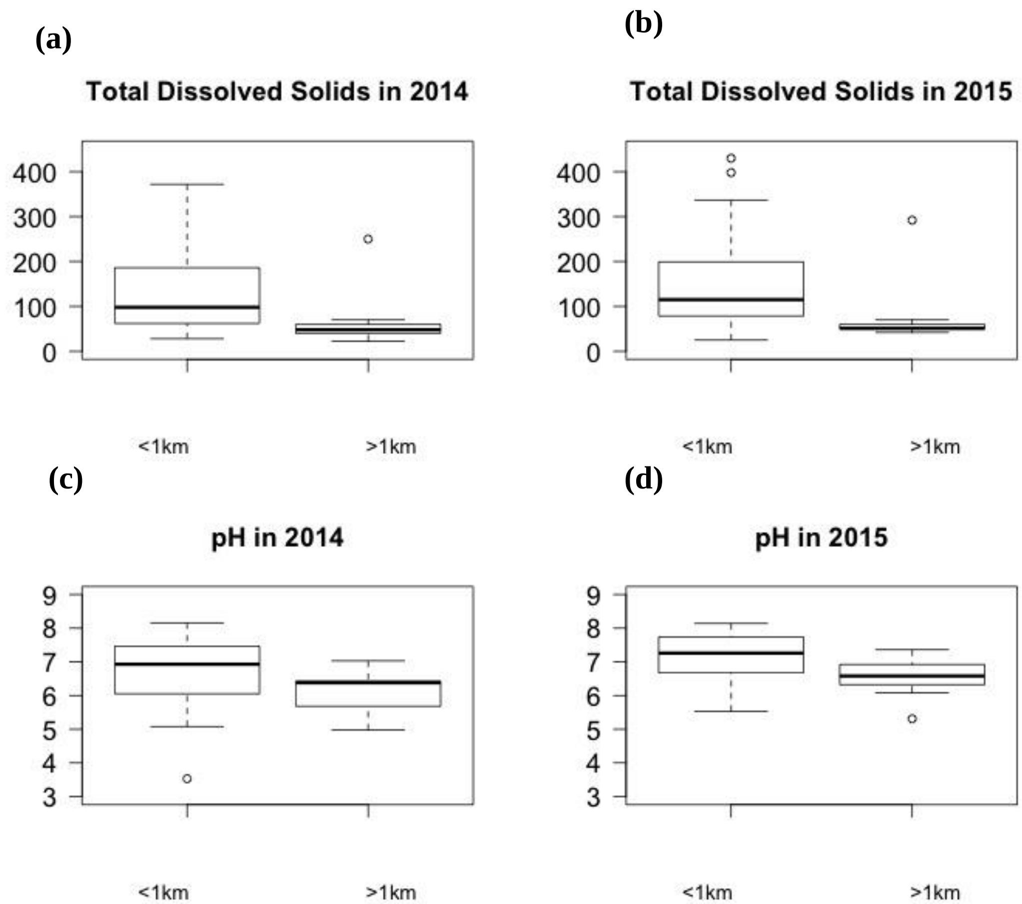

Figure 4.2 Total dissolved solids and pH boxplots are shown for years 2014 and 2015. Both TDS (a and b) and pH (c and d) show more variation and higher medians in lakes <1 km from the Dempster Highway.

4.2.3 Major Ions

Major ions that showed a potentially significant difference with increasing distance from the highway included calcium (Ca^{2+}), magnesium (Mg^{2+}), hardness, nitrate (NO_3-N), nitrate/nitrite ratio (NO_3/NO_2-N) and sulphate (SO_4^{2-}). The 2014 data showed that Ca^{2+}, Mg^{2+}, hardness and SO_4^{2-} decreased significantly with increasing distance from the Dempster Highway (t=2.5541, *p-value*=0.01685, t=2.4618, *p-value*=0.02077, t=2.5942, *p-value*=0.01537, t=2.0142 and *p-value*=0.05444, respectively). NO_3-N and NO_3/NO_2-N showed no significant difference between lakes <1 km and >1 km from the Dempster Highway in 2014 (t=1.0034, *p-value*=0.3249, t=1.0054 and *p-value*=0.3249, respectively). In the 2015 data only SO_4^{2-} was deemed as having no significant difference between lakes <1 km and those >1 km from the Dempster Highway (t=1.9152, *p-value*=0.6653). Boxplots of these major ions also showed that the medians in 2014 and 2015 were higher in lakes <1 km from the Dempster Highway (Figure 4.3a-d; Figure 4.4a-d; Figure 4.5a-d).

Ca^{2+}, hardness, NO_3-N and NO_3/NO_2-N peaked in DEMPLK 1 with values of 96.40 mg/L, 380 mg/L, 0.14 mg/L and 0.15 mg/L, respectively. Mg^{2+} and SO_4^{2-} peaked in lake FM50 (60 m from Dempster Highway) at 26.30 mg/L and 234 mg/L, respectively. Minimums for Ca^{2+}, Mg^{2+} and hardness were recorded in lake FM05 (430 m from Dempster Highway) with values of 430 mg/L, 0.50 mg/L and 4.60 mg/L, respectively. NO_3-N and NO_3/NO_2-N minimums occurred in several lakes, including FM05, FM04 (670 m), FM15 (730 m), FM19 (4.82 km), DEMPLK 3 (5.48 km), DEMPLK 4 (5.86 km), FM27 (7.66 km), FM28 (18.92 km), FM24 (18.93 km) and FM06 (23.62 km) at 0.02 mg/L.

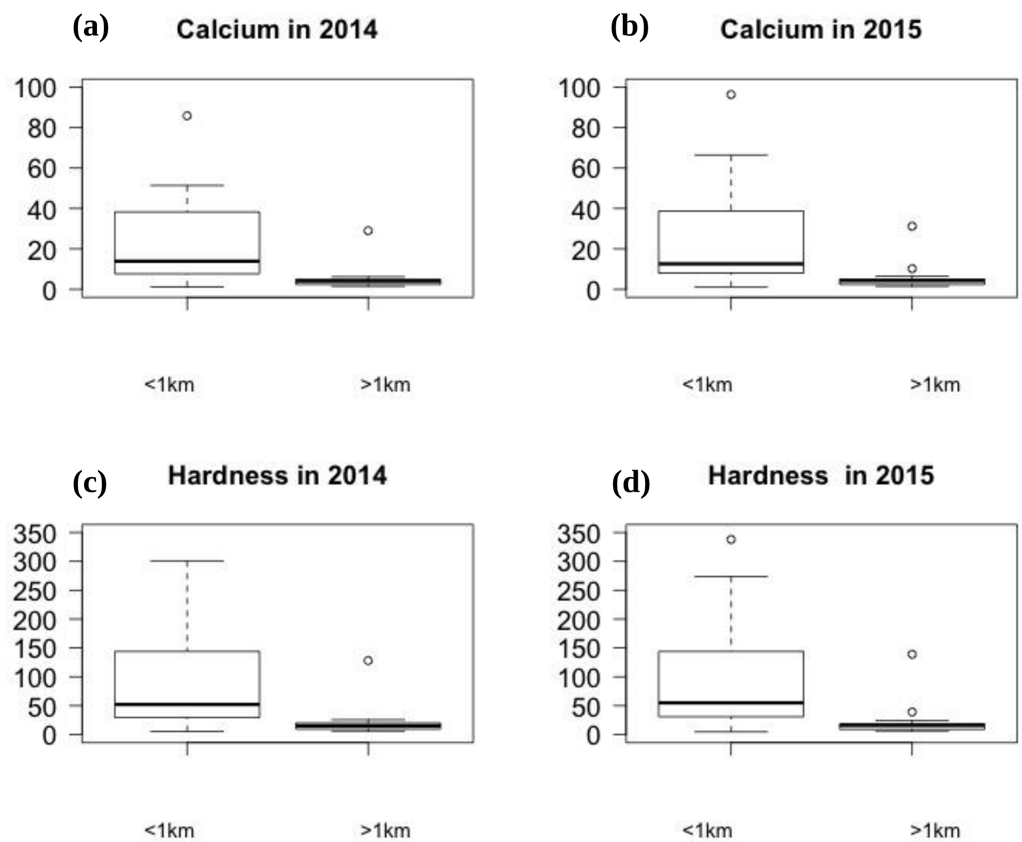

Figure 4.3 Ca^{2+} and hardness boxplots for both 2014 and 2015. Both Ca^{2+} (a and b) and hardness (c and d) show more variation and higher medians in lakes <1 km from the Dempster Highway.

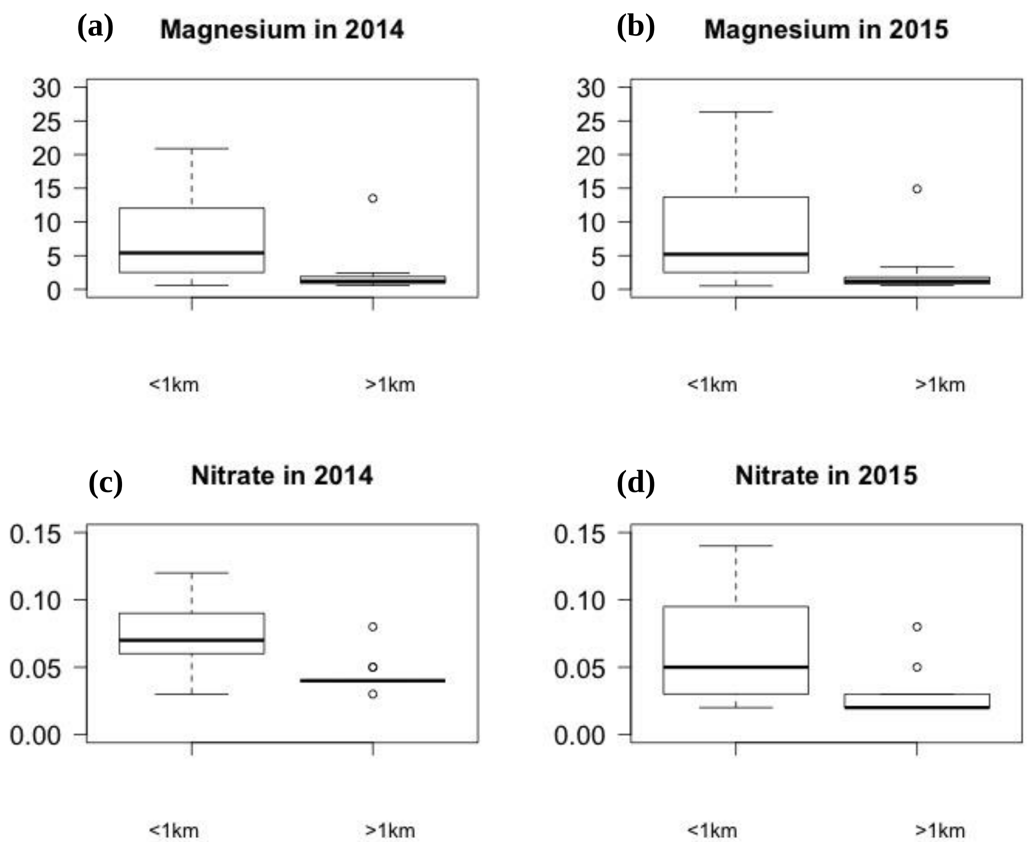

Figure 4.4 Mg^{2+} and NO_3-N boxplots in years 2014 and 2015. Both Mg^{2+} (a and b) and NO_3-N (c and d) show more variation and higher medians in lakes <1 km from the Dempster Highway.

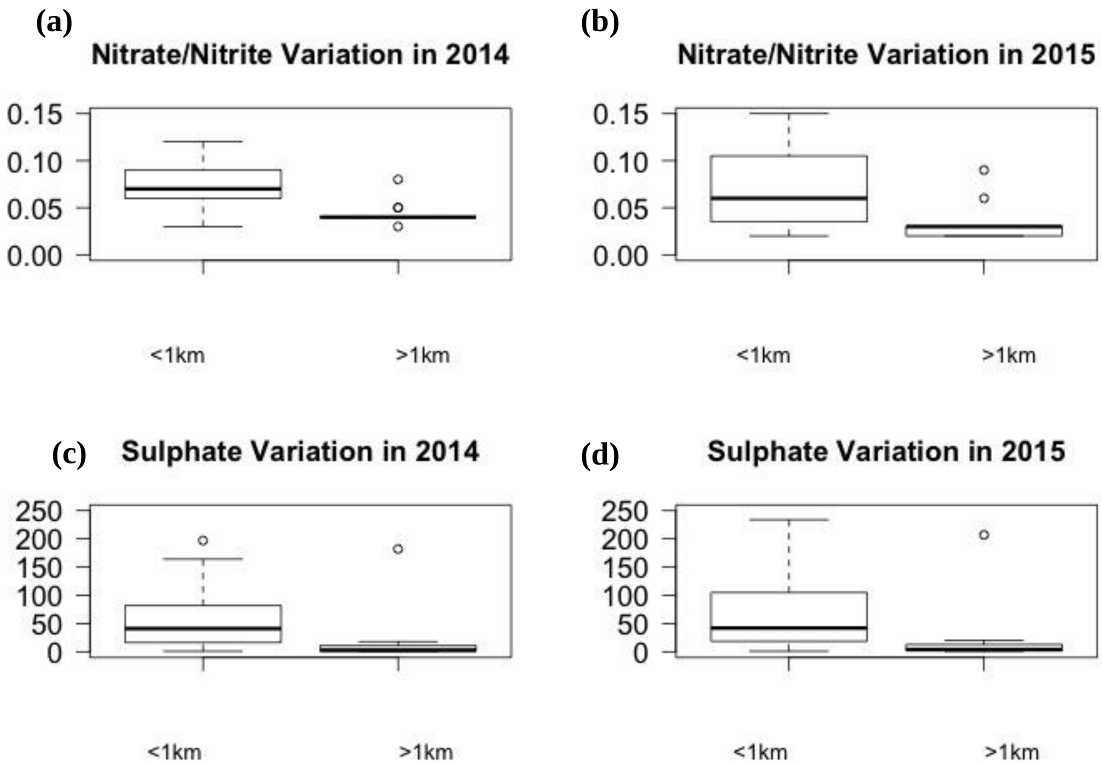

Figure 4.5 NO_3/NO_2-N and SO_4^{2-} boxplots for years 2014 and 2015. Both NO_3/NO_2-N (a and b) and SO_4^{2-} (c and d) show more variation and higher medians in lakes <1 km from the Dempster Highway.

4.2.4 Metals

Only Sr^{2+} was significantly higher in lakes <1 km from the Dempster Highway (t=2.4188; p=0.02287; (2014) and t=2.4521; p=0.02123; (2015)). The concentration of Sr^{2+} varied from 4.80 µg/L to 275 µg/L within the 28 study lakes. The lowest concentration was found in FM05 (4.80 µg/L) and the highest in DEMPLK 1 (275 µg/L), similar to many of the other variables discussed thus far. Boxplots also determined that the medians for Sr^{2+} were higher for lakes <1 km from the Dempster Highway in both 2014 and 2015 (Figure 4.6 a and b).

Lakes within 1 km to the Dempster Highway had higher concentrations for a number of water chemistry variables, including alkalinity, conductivity, TDS, Ca^{2+}, Mg^{2+}, hardness, pH, NO_3-N, NO_3/NO_2-N, SO_4^{2-} and Sr^{2+}. It was evident that lakes within 1 km of the Dempster Highway had a higher variability in the above-mentioned water chemistry variables, and that with increasing distance from the Dempster Highway the water chemistry variables decreased significantly. This decrease was evident within the two impacted lakes and one control lake. For most variables, FM02 had higher measured values when compared to FM04 and FM06, while FM06 had the lowest measured values for most variables mentioned above. Boxplots for these specific water chemistry variables showed that medians in both the 2014 and 2015 data were consistently higher in lakes <1 km from the Dempster Highway when compared with lakes >1 km from the highway.

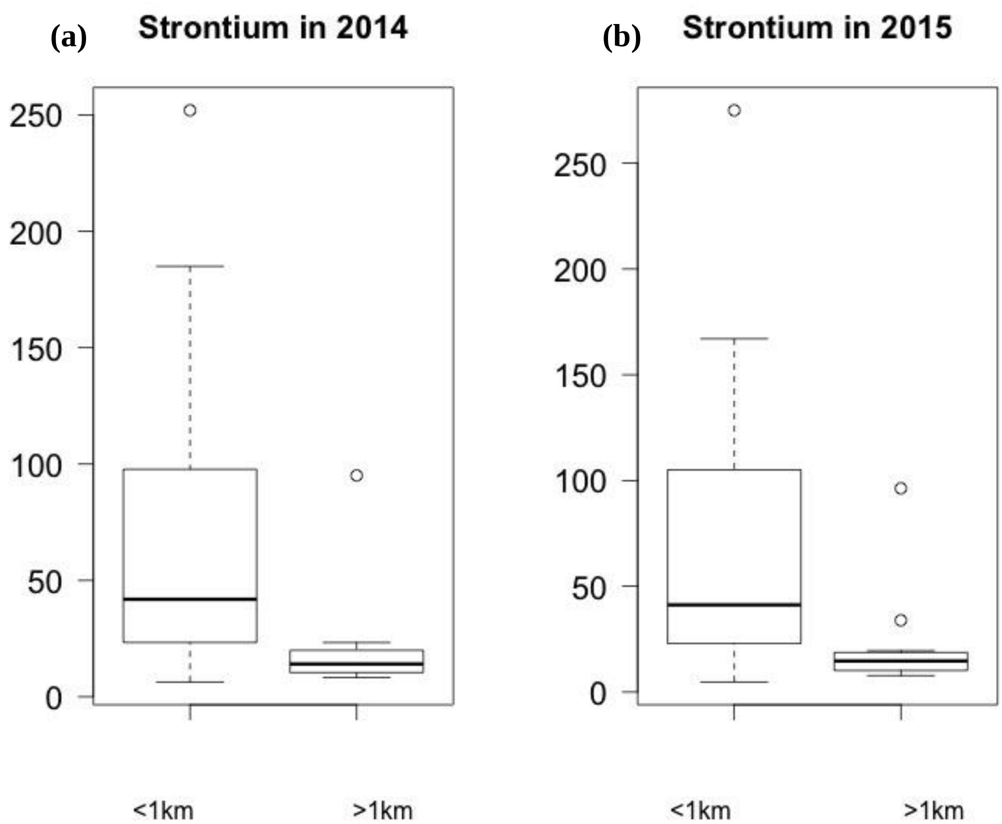

Figure 4.6 Variations in Sr^{2+} in years 2014 (a) and 2015 (b). Sr^{2+} shows more variation and higher medians in lakes <1 km from the Dempster Highway in both 2014 and 2015.

4.3 Elemental Variations

4.3.1 Dempster Highway Gravel

In order to focus the elemental analysis in the lake sediment cores collected for this study, elemental variations were first determined for a sample of gravel and road dust collected from the surface of the Dempster Highway on the Peel Plateau. A suite of 57 elements were analysed from the road sample and those that were highest in abundance (highest counts per second (cps)) were examined in greater detail to determine how they vary throughout each lake sediment core. The elements that showed the highest cps are provided in Table 4.2.

The elements that were found to have high cps in the sample collected from the Dempster Highway gravel included, potassium (K^{+}), calcium (Ca^{2+}), titanium (Ti^{3+}), iron (Fe^{2+}), strontium (Sr^{2+}), and terbium (Tb^{2+}). These elements had mean values of 1,944.62 cps, 30,237.91 cps, 1,886.08 cps, 167,914.69 cps, 1,841.60 cps and 1,454.37 cps, respectively (Table 4.2). Ca^{2+} and Fe^{2+} have the highest cps within the gravel from the Dempster Highway, while Tb^{2+} and Sr^{2+} have the lowest abundance of these elements.

The elemental profiles for elements that were found to have high cps within the gravel from the Dempster Highway were plotted for lakes FM02, FM04 and FM06. The data that was attained through the ITRAX X-ray fluorescence core scanning system shows the cps for each element at every 0.05 cm interval. In order to focus on the areas before and after the construction of the Dempster Highway, only the values for directly before and after construction will be plotted to show changes in the data throughout each lake sediment core. The full graphs can be found for each variable (K^{+}, Ti^{3+}, Fe^{2+}, Tb^{2+}, Sr^{2+} and Ca^{2+}) in Appendix III.

Table 4.2 Elemental analysis of the gravel and road dust sample collected from the surface of the Dempster Highway on the Peel Plateau within the study region. The elements that are of high abundance were determined using the ITRAX X-ray fluorescence core scanning system at McMaster University. Each element was measured as counts per second (cps) with higher cps meaning higher abundance of the element within the gravel.

Element	Type (Periodic Table)	Average cps Within Gravel
K^{+}	Alkali Earth	1,944.62
Ca^{2+}	Alkali Earth	30,237.91
Ti^{3+}	Transition Metal	1,886.08
Fe^{2+}	Transition Metal	167,914.69
Sr^{2+}	Alkaline Earth	1,841.60
Tb^{2+}	Rare Earth	1,454.37

In addition to plots, a one-way Analysis of Similarities (ANOSIM) test (Clarke, 1993) was performed on K^{+}, Ti^{3+}, Fe^{2+}, Tb^{2+}, Sr^{2+} and Ca^{2+} in each lake sediment core to determine if there was a significant difference before or after the Dempster Highway construction.

To fully understand the potential impacts of calcareous road dust from the Dempster Highway and from possible climate warming, chronologies of FM02, FM04 and FM06 were completed on the 2014 cores. ^{210}Pb dating was used to estimate the dates of the 2014 cores by using a constant rate of supply (CRS) model (Appleby, 2001; Binford, 1990) (Appendix V). ^{137}Cs was also used, where the peak in ^{137}Cs corresponds to the global ban on atmospheric nuclear testing in 1963 (Appleby, 2001). Since the ITRAX X-ray fluorescence data and the algal palynomorph counts are from the 2015 cores, the dates for the 2014 and 2015 cores had to be matched using LOI, so there is some uncertainty and this data should be interpreted cautiously.

4.3.2 Physical Sedimentology of Lake Sediment Cores FM02, FM04 and FM06

The results from the one-way analysis of similarities (ANOSIM) test (Clarke, 1993), was performed on several elements throughout the three lake sediment cores. It was determined that cps of Ca^{2+} differed significantly before and after construction of the Dempster Highway in both lake sediment cores FM02 and FM04 (R=0.33, *P-value*=0.001 and R=0.677, *P-value*=0.001, respectively; Table 4.3). $Fe^{2+}$was also significantly different before and after construction in lake sediment core FM04 (R=0.412, *P-value*=0.001). In lake sediment core FM06, there was a noted significant difference when

Table 4.3 Results from the ANOSIM test showed Ca^{2+} was significantly different in lakes FM02 and FM04 before and after construction of the Dempster Highway. Fe^{2+} in lake sediment core FM04 is also considered significantly different before and after the Dempster Highway construction.

				FM02			
	Potassium	Calcium	Iron	Strontium	Terbium	Titanium	All Elements
R-value	0.041	0.33	0.085	0.087	0.047	0.068	0.184
P-value	0.006	0.001	0.001	0.001	0.002	0.001	0.001
				FM04			
	Potassium	Calcium	Iron	Strontium	Terbium	Titanium	All Elements
R-value	0.229	0.677	0.412	0.027	0.019	0.272	-0.018
P-value	0.001	0.001	0.001	0.017	0.05	0.001	9.97
				FM06			
	Potassium	Calcium	Iron	Strontium	Terbium	Titanium	All Elements
R-value	0.29	0.097	0.154	0.018	0.037	0.362	0.466
P-value	0.001	0.001	0.001	0.002	0.001	0.001	0.001

all elements before and after construction were tested against one another (*R*=0.466, *P-value*= 0.001).

Graphical representation of the lake sediment cores showed that since ~AD1880 (FM02) (Figure 4.7), K^+, Ti^{3+}, and Sr^{2+} have been decreasing over time, while Fe^{2+}, Tb^{2+} and Ca^{2+} have been increasing over time. Paired with the ANOSIM tests, it helps determine that Ca^{2+} (being significantly different before and after construction) has increased since the construction of the Dempster Highway. In lake sediment core FM04, since ~AD1900, K^+, Ti^{3+}, Tb^{2+} and Sr^{2+} appear to have been decreasing, and both Fe^{2+} and Ca^{2+} have been increasing (Figure 4.8). The control lake (FM06) showed decreasing K^+, Ti^{3+}, Sr^{2+} and Ca^{2+} over time, and both Fe^{2+} and Tb^{2+} have increased (Figure 4.9) but ANOSIM showed no significant differences in these elements before and after the construction of the Dempster Highway.

Overall**,** chemical and physical proxies of the lake water and lake-bottom sediment were analysed to determine the response of the aquatic communities within an area that has potentially increased dust deposition. Results of the water chemistry showed that lakes within 1 km of the Dempster Highway generally had a higher variability and lakes with increasing distance from the Dempster Highway had significantly lower values of alkalinity, conductivity, TDS, pH, Ca^{2+}, Mg^{2+}, hardness,NO_3-N, NO_3/NO_2-N, SO_4^{2-} and Sr^{2+}. The physical sedimentology showed minimal indication of changes within K^+, Ti^{3+}, Tb^{2+}, Fe^{2+}, Sr^{2+} or Ca^{2+} in all three cores (FM02, FM04 and FM06). Large increases and decreases in the elements did not occur around the time of the Dempster Highway construction, most occurred approximately 15 years after construction and most elements

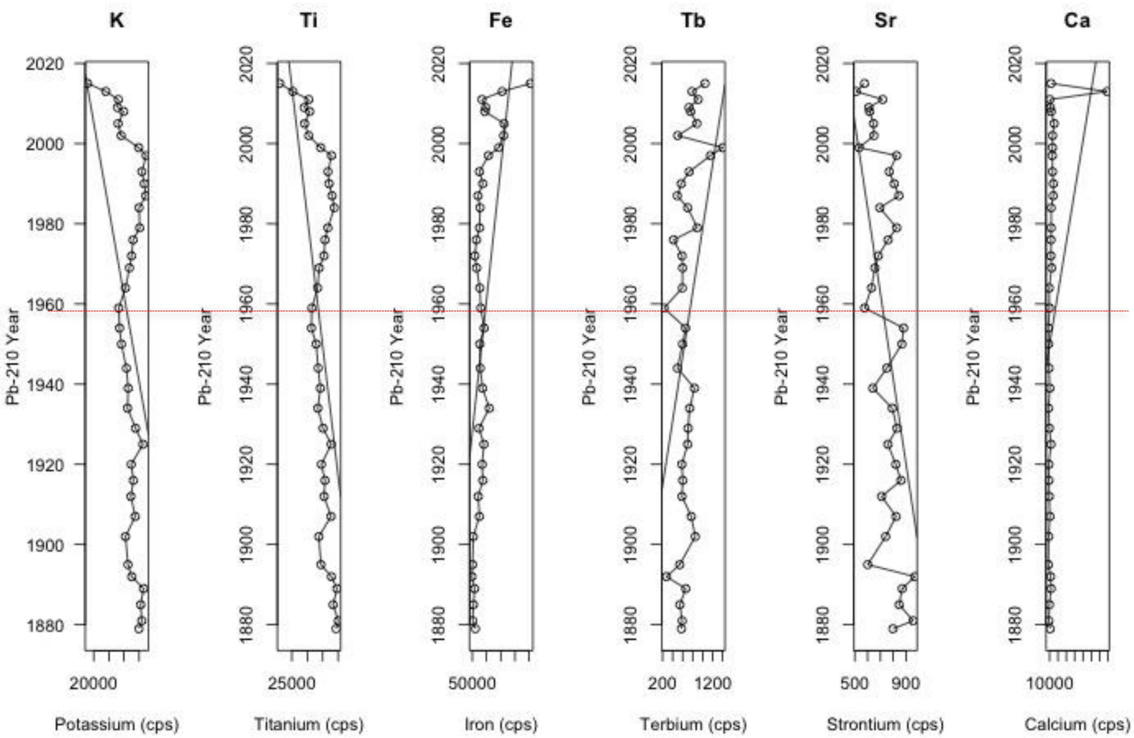

Figure 4.7 The ITRAX elemental profiles for lake FM02. Potassium (K^{+}), titanium (Ti^{3+}), iron (Fe^{2+}), terbium (Tb^{2+}), strontium (Sr^{2+}) and calcium (Ca^{2+}) elemental variations are plotted to show the impact of the Dempster Highway on the sediment record. Construction of the Dempster Highway began in 1958, which is depicted by the solid red line.

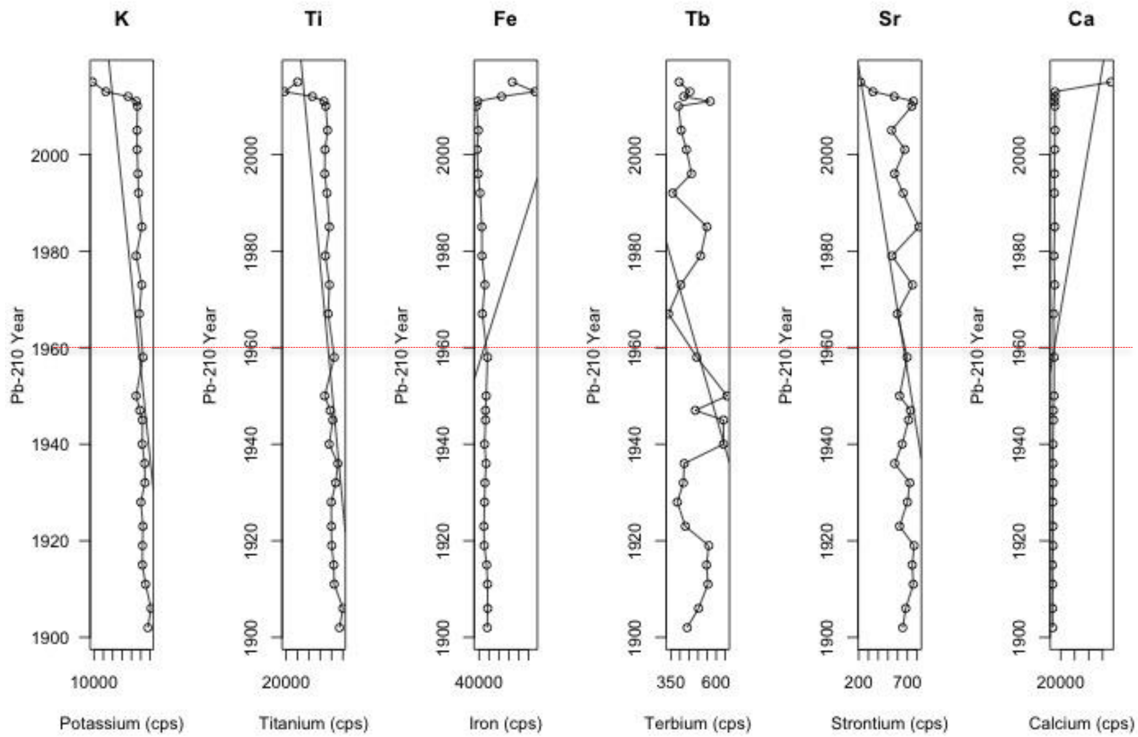

Figure 4.8 The ITRAX elemental variations for lake FM04. Potassium (K^{+}), titanium (Ti^{3+}), iron (Fe^{2+}), terbium (Tb^{2+}), strontium (Sr^{2+}) and calcium (Ca^{2+}) elemental variations are shown between 2015 and approximately the year 1900. The graph is split with the red line at ~1958; the year construction of the Dempster Highway began.

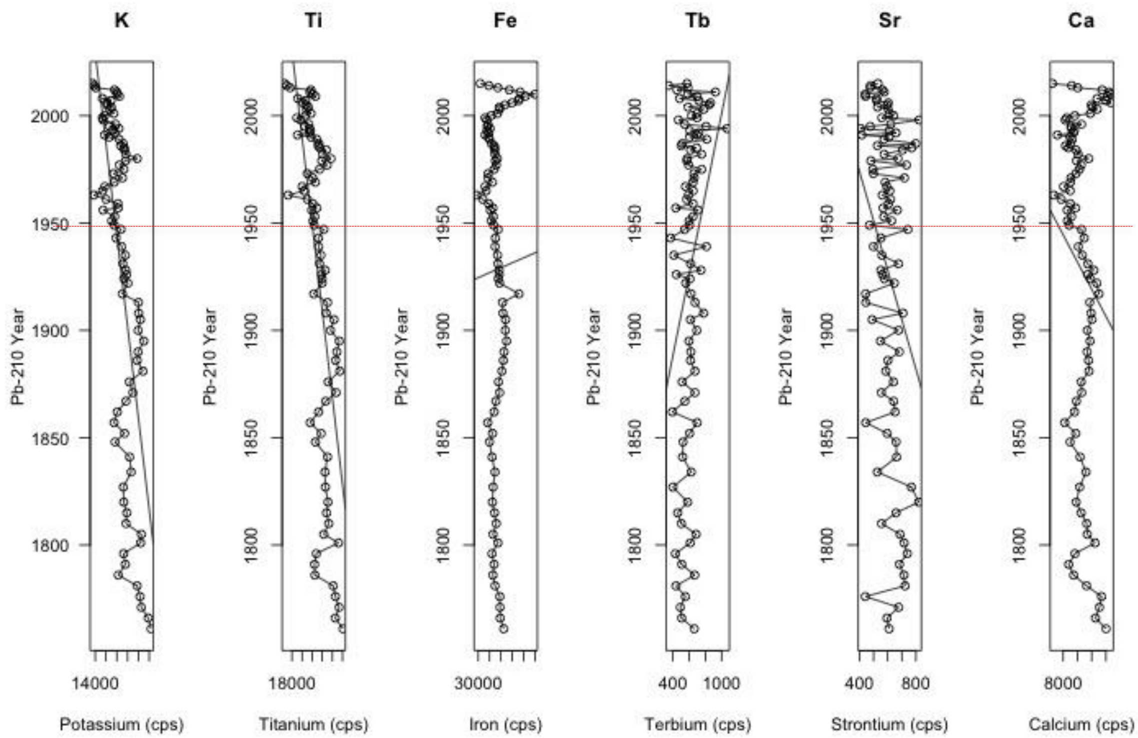

Figure 4.9 The ITRAX elemental profiles for the control lake, FM06. Elements were found to have high counts per second (cps) throughout the gravel along the Dempster Highway have been plotted for before and after construction. The red line represents the year that construction of the Dempster Highway began (~1958).

recorded decreases rather than increases in their abundance throughout the cores. Fe^{2+} recorded a higher value within FM04 after construction, while in FM02 and FM06 there were no recorded changes. Ca^{2+} was significantly higher after construction in both cores FM02 and FM04.

Chapter 5

Discussion

5.1 Impacts of Dust Loading from The Dempster Highway on the Water Chemistry in Surrounding Small Lakes and Ponds

The first objective of this research was to identify if dust loading from the Dempster Highway has altered the water chemistry (i.e. pH, conductivity, concentration of major ions, etc.) of lakes located in close proximity to the highway. The largest difference in the water chemistry variables was found between lakes that were <1 km from the highway and those >1 km from the highway. Alkalinity, conductivity, TDS, hardness, Mg^{2+}, Ca^{2+}, pH, NO_3-N, NO_3+NO_2-N, SO_4^{2-} and Sr^{2+} were all measured to be higher in lakes that were within 1 km of the Dempster Highway.

Of the 15 lakes/ponds <1 km from the highway, eight exhibited much higher values for all water chemistry variables; two of these had retrogressive thaw slumps on their north side (FM03 and DEMPLK1). DEMPLK1 also recorded maximum values for most of the water chemistry variables (excluding Mg^{2+} and SO_4^{2-}). Lakes FM04, FM05, FM10, FM12, FM14, FM15 and FM16, <1 km from the highway, exhibited low values for most nutrients, major ions and some metals (Appendix I). Despite being easily visible from the highway Lake FM10 (Figure 5.1a) exhibited very low values for all water chemistry variables. Tall shrubs and trees around FM10 could trap some of the dust before it reaches the lake, causing the water chemistry variables in this particular lake to remain low. In lake FM02, also visible from the highway (Figure 5.1b) there are no tall shrubs or trees, allowing dust to reach this lake easily. This could explain the lower values for water chemistry variables in Lake FM10, and potentially other lakes that

Figure 5.1 Lake FM10 **(a)** and lake FM02 **(b)** vegetation differences. FM10 is clearly visible from the Dempster Highway, although there appears to be tall shrubs and large spruce trees surrounding it, which could hinder the amount of dust that would reach this lake. FM02 has only short grasses and shrubs and is lacking tall trees in its surroundings. Since these two lakes are the same distance from the Dempster Highway, the difference in surrounding vegetation could be one reason why their water chemistry parameters are so different. (Images from Google Earth, 2016).

exhibited low values for the same water chemistry variables.

There are several possible explanations for the lower values for most water chemistry variables in lakes FM04, FM05, FM10, FM12, FM14, FM15 and FM16 compared to other lakes <1 km from the Dempster Highway. Increased evaporation or possible groundwater infiltration in any of the lakes could explain the differences. Isotopic analysis would give an understanding of the relative importance of source water type (rain versus snow) and evaporation (Turner et al., 2010; Turner et al., 2014). Evaporation has been identified as a strong driver of lake water level reductions in northern Canada (e.g., Labrecque et al., 2009; Bouchard et al., 2013). Effects due to climate variation (e.g. evaporation, increased/decreased precipitation, etc.) could be lake-specific (Plug et al., 2008; MacDonald et al., 2012); some of the lakes could be undergoing increased amounts of evaporation. This would cause the variables to be more concentrated, which could lead to higher values for most water chemistry variables in lakes FM02, FM50, FM17, FM11, DEMPLK2 and FM18. Groundwater flow could cause dilution of variables including TDS, pH, conductivity and concentrations of major ions in lakes FM04, FM05, FM10, FM12, FM14, FM15 and FM16.

The laboratory results also showed that lakes with retrogressive thaw slumps within their catchment, (FM03, DEMPLK1 and FM29), had higher levels of alkalinity, conductivity, TDS, hardness, and several major ions. Several studies have highlighted the importance of retrogressive thaw slump activity on lake water chemistry, suggesting that retrogressive thaw slumps will alter the nearby aquatic ecosystems by increasing the concentration of major ions in the water (Kokelj et al., 2005; Kokelj et al., 2013; Malone et al., 2013; Thienpont et al., 2013). In addition, it was suggested that retrogressive thaw slumps could alter the water chemistry of lakes for decades once the slump is no longer active (Kokelj et al., 2005; Thienpont et al., 2013).

The water chemistry was examined to determine if calcareous road dust impacted the aquatic biota in lakes surrounding the Dempster Highway. The United States Environmental Protection Agency (2012) determined that conductivity levels close to or over 500 μS/cm are inhospitable environments for many fish species and microinvertebrates. DEMPLK 1 (640 m) and FM50 (60 m) had conductivity values of 620 μS/cm and 565 μS/cm, respectively, which could be potentially harmful to microorganism populations, although many microscopic algae can tolerate marginal marine environments. The Fundamentals of Environmental Measurements (2016) deems a lake uninhabitable when TDS levels exceed 2000 mg/L, which was a value not reached in any of the lakes along the Dempster Highway.

Results for water chemistry showed that the dust loading from the Dempster Highway is likely affecting certain water chemistry variables within some of the small lakes and ponds that are within 1 km of the highway. Lakes >1 km away are generally unaffected by dust loading from the highway. Lakes with retrogressive thaw slumps in their catchments have higher readings of TDS, hardness, pH and various ions due to the large inputs of sediment that are seen with retrogressive thaw slump activity (Kokelj et al., 2005; Kokelj et al., 2013, Thienpont et al., 2013), and these effects were seen in lakes up to 20 km away from the Dempster Highway. Without dust traps to determine the amount of dust that reaches the lakes on a seasonal basis, it is unknown what the direct cause is for heightened water chemistry values in lakes that are <1 km from the Dempster Highway.

It is difficult to determine whether or not a lake is healthy or unhealthy using synoptic measurements of water chemistry. The sediment should be looked at with a paleolimnological approach to determine how biota, such as algae, have changed over time, to fully understand the impacts of calcareous road dust on the aquatic communities.

5.2 Using Paleolimnology to Track the Development of the Dempster Highway

The ITRAX X-ray fluorescence core scanning system was developed to determine elemental variations throughout sediment cores. The second objective of this research was to determine whether or not the dust loading in lakes in close proximity to the Dempster Highway showed changes in specific elemental variations before and after the construction of the highway. An initial scan of dust and gravel from the Dempster Highway roadbed using the ITRAX X-Ray Fluorescence scanning system identified high amounts of K^{+}, Ti^{3+}, Fe^{2+}, Tb^{3+}, Sr^{2+} and Ca^{2+} in the roadbed materials; it was thus hypothesised that these elements would increase in the lake sediment records from lakes nearest to the highway corridor after construction of the highway.

In one of the impacted lake sediment cores, FM02, Fe^{2+} and Ca^{2+} are notably higher after the construction of the Dempster Highway (Figure 4.10a; Figure 4.12a), but do not begin to increase steadily until ~2000. In the lake sediment core from FM04, only Ca^{2+} is significantly higher (Figure 4.12b) after construction of the Dempster Highway. The other elements (K^{+}, Ti^{3+}, Tb^{2+} and Sr^{2+}) showed significant decreases since the construction of the Dempster Highway. In any landscape, elements will vary on a seasonal and yearly basis depending on the climate and what sediments are available in the area. These types of fluctuations are visible in the full core plots that can be found in

Appendix III. As there are only notable increases in Fe^{2+} and Ca^{2+} in the impacted lake sediment cores, there is no clear evidence that a signal related to the construction of the Dempster Highway occurs in the lake sediment cores. The control lake, FM06, did not show evidence of increased values for any of the elements, suggesting there is no dust loading in the control lake. The full-length cores showed evidence that there are differences in the surrounding environments of FM02, FM04 and FM06. Lake sediment core FM02 showed more variability within the elements than cores FM04 and FM06, suggesting that the environments surrounding the lakes are different.

It is unlikely that the reason for the lack of a dust-loading signature is due to wind patterns within the area. In Fort McPherson, the prevailing wind direction (from AD 1985 to AD 2016) is north, to north-north-west in both the cold and warm seasons (Figure 5.2). This should indicate that the lakes south of the Dempster Highway would potentially experience more dust deposition than those north of the highway. Since FM04 is south of the highway, there could be more dust loading in this lake than FM02 and FM06, which are north of the highway. This is not the case, which could be because lake FM04 is 670 m from the Dempster Highway, while FM02 is only 50 m north of the highway. It is difficult to determine whether the direction of the wind had an influence on the deposition of dust into lakes FM02, FM04 and FM06 due to their directions from the Dempster Highway as well as their distances.

The construction and continued operation of the Dempster Highway does not leave an identifiable signature in the sediment record based on elemental variations. The dust that is being deposited in the lakes may be enough to alter the water chemistry parameters on a short-term basis, but no long-term influence was detectable in the

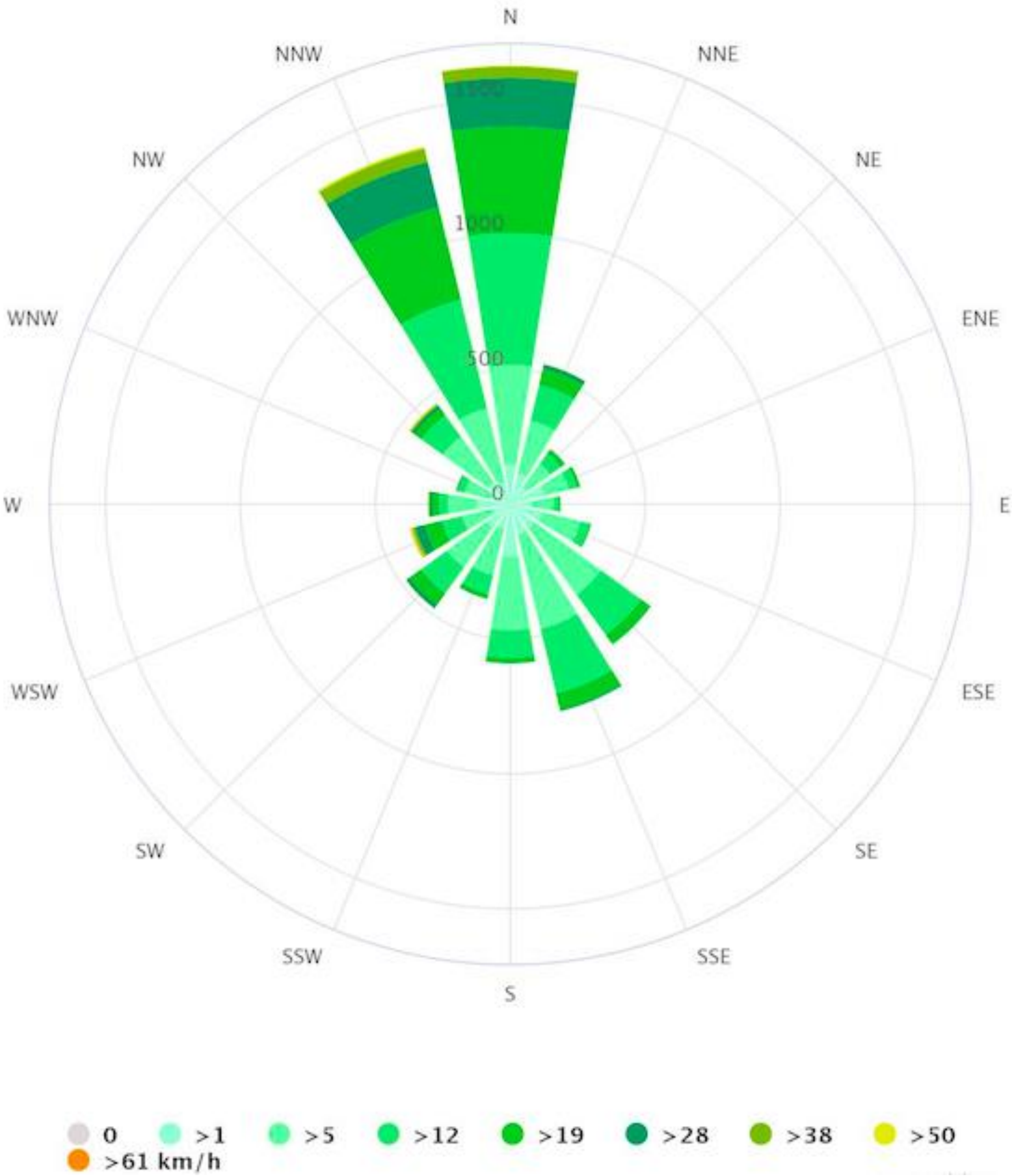

Figure 5.2 A wind rose for Fort McPherson displays the prevailing wind direction (per day) over a 31-year period (AD 1985-AD 2016) and average wind speed in km/h. The predominant winds come from the north and north-north-west at Fort McPherson. (From Meteoblue, 2016).

sediment for our study lakes using the ITRAX X-ray fluorescence core scanning system.

5.3 The Algal Palynomorph Assemblages Before the Onset of Regional Warming (Zone 1)

As part of the work on the impacts of dust from the Demspter Highway on small lake systems, we were also interested in the impact dust loading may have on the ecosystems in these lakes, especially non-pollen paynomorphs and green algae in particular. To examine these potential impacts, the FM-02 sediment core was processed for algal paynomorphs. This data (Caitlin Garner, unpublished data) is presented in its entirety in Appendix IV. The processing of sediment for the analysis of algal palynomorphs was undertaken by Caitlin Garner with the assistance of the candidate (Rebecca Gunter). Caitlin Garner carried out all identifications and counts of the algal palynomorph data. Rebecca Gunter provided the interpretations of the algal palynomorph data that follows.

The Little Ice Age was a period between ~AD 1375 and ~AD 1820 when mean annual temperatures in Europe and North America were approximately 2-3°C cooler than at present (Mann, 2002). The Little Ice Age was not one prolonged period of cold, but rather two phases. From ~AD 1375 into the late 1400's, it was quite cold with a warmer period during the 1500's (Moore et al., 2001). After the 1500's, the climate cooled again, with the coldest period between ~AD 1645 and ~AD 1715 (Oosthoek, 2015). During this time, it is likely that there were reduced nutrients in the waters and longer periods of ice cover on the lakes, making it hard for some genera to multiply and even survive. On the other hand, certain species do thrive in oligotrophic and slightly acidic conditions, which likely would have been the case during this period.

Within Zone 1, which would have likely coincided with the Little Ice Age, there is an increase in the species diversity (Figure 5.3) that includes the colonial chlorophyte *Botryococcus braunii*, and desmids *Cosmarium spp*., *Euastrum spp*., and *Staurastrum spp*. The only genus not identified until after the Little Ice Age is *Pediastrum*. There are no large shifts in Zone 1 between genera or species dominance, suggesting this was a period before regional warming and the influx of nutrients and major ions from surrounding sediments and decaying organic matter. Dominating this section of the core are the above-mentioned genera, but more specifically *Euastrum bidentatum, E. cuneatum*, *E. didelta*, *Staurastrum gracile,* and *Cosmarium botrytis.* These species represent eutrophic to mesotrophic habitats that range from acidic to neutral pH levels (Table 5.1).

5.3.1 Potential Impacts of Regional Warming on Algal Palynomorph Assemblages in Lake FM02

After the Little Ice Age (post ~AD 1850), temperatures slowly increased. After ~AD 1850 regional warming began across the Canadian Arctic due to recovery after the Little Ice Age and within the second half of the 20th century warming was likely due to the Great Acceleration. The Canadian Arctic has experienced accelerated warming (~1°C per decade vs. globally at 0.25°C per decade since ~AD 1960 (IPCC, 2016)) and these high-latitude ecosystems will experience stronger shifts and heightened impacts due to Arctic amplification (Hinzman et al., 2005; Serreze and Barry, 2011).

Analyst: Cait Garner

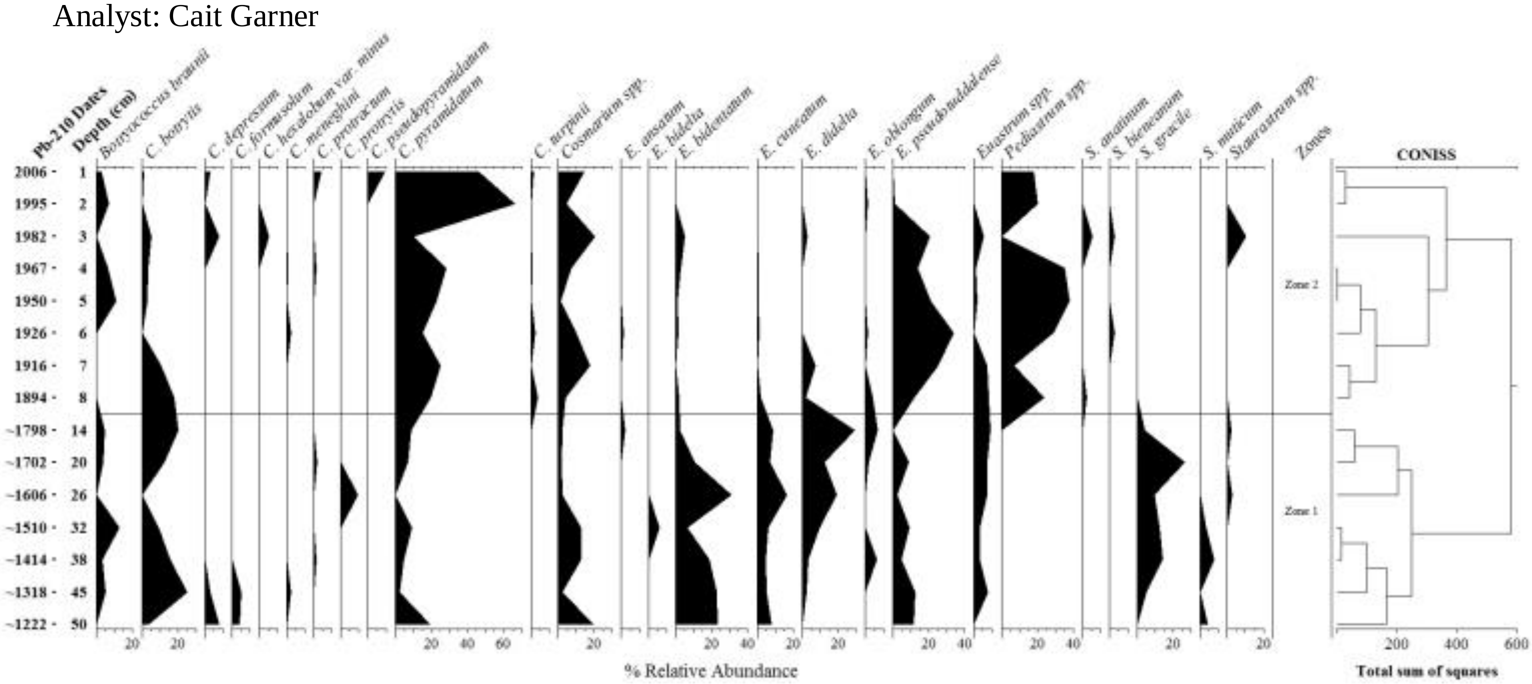

Figure 5.3 The percent relative abundance of all counted NPP throughout the FM02 impacted core (Caitlin Garner, unpublished data). NPP were counted and relative abundance was calculated using the number of *Lycopodium clavatum* spores present in each slide. *Pediastrum spp.*, do not appear until the top of Zone 1 (14 cm, ~ AD 1798). *Cosmarium pyramidatum* increases consistently throughout both Zone 1 and Zone 2. *Euastrum spp.*, and *Staurastrum spp.*, completely disappear within the top 2 cm of the core (Zone 2). *Botryococcus braunii* exhibits no large changes throughout the entire core. No marked zonation occurs around the construction period of the Dempster Highway, according to CONISS. Analysis was performed by Caitlin Garner and ecology was based on Jankovska and Komarek, 2000; Komarek and Jankovska, 2001; and Stastny, 2010.

Table 5.1 Algal palynomorphs that were identified in lake sediment core FM02 by Caitlin Garner (C. Garner, unpublished data). Recorded here are their life form (ben – benthic, pla – planktonic), as well as ecological features including the trophic state of their habitat (eu – eutrophic, mes-mesotrophic, oli-oligotrophic) and acidity (aci-acidic, neu-neutral, alk-alkaline). (Jankovska and Komarek, 2000; Komarek and Jankovska, 2001; Stastny, 2010).

Species	Trophic state of the habitat	Acidity	Life form
Botryococcus			
Botryococcus braunii Kutzing	mes-eu	neu-alk	pla
Desmids			
Cosmarium botrytis Ralfs	mes-eu	aci-neu	ben
Cosmarium depressum (Nageli) P. Ludell	mes	aci-neu	ben
Cosmarium formusolum Hoff	eu-mes	aci-alk	ben-pla
Cosmarium meneghini Ralfs	mes-eu	neu-aci	ben
Cosmarium protractum (Nageli) De Bary	eu	alk	ben
Cosmarium pseudopyramidatum P. Lundell	oli-mes	aci	ben
Cosmarium pyramidatum Ralfs	oli-mes	aci	ben
Cosmarium turpinii Breb	mes-eu	aci-alk	ben
Euastrum ansatum Ralfs	mes-oli	aci	ben
Euastrum bidentatum Nageli	mes	aci-neu	ben
Euastrum oblongum Ralfs	mes	aci	ben
Euastrum pseudotuddalense Messikommer	mes	??	ben
Staurastrum anatinum Cooke & Wills	??	??	pla
Staurastrum bieneaunum Rabenh	mes	aci	ben
Staurastrum gracile Ralfs	mes	aci	ben
Staurastrum muticum Ralfs	mes	aci	ben

As the temperature in the Canadian Arctic continues to warm, there will be further impacts on the environment. One of the repercussions of increasing temperatures is the thawing of permafrost, which causes changes to the landscape and ultimately, the addition of large amounts of nutrients and elements into surrounding lakes and ponds (Kokelj et al., 2013). As ice-rich permafrost thaws, landscapes can experience drastic changes including development of thermokarst lakes and ponds and retrogressive thaw slumps. Retrogressive thaw slumps are highly erosive features in periglacial environments. The materials released from retrogressive thaw slumps will alter both the physical and chemical parameters of nearby aquatic systems (Kokelj et al., 2013; Malone et al., 2013; Thienpont et al., 2013).

Increasing air temperatures lead to warmer water temperatures in lakes and ponds. With increasing water temperatures, there is a chance for new genera or species of algal palynomorphs to appear or flourish. Also, the decomposition in these small lakes and ponds will increase with warmer water temperatures (Kowalski, 2014). The increase in decomposition will cause an increase in nutrient availability within the lake, can cause a shift to a mesotrophic or eutrophic lake environment, and will increase biochemical oxygen demand, resulting in lower dissolved oxygen concentration, particularly in the bottom water. Rouse et al. (1997) also concluded that warmer temperatures would affect the chemical and mineral makeup of lakes, as well as the nutrient status, possibly changing the composition of algal palynormophs and ultimately becoming detrimental to the entire food chain.

It was expected that species diversity would be highest within Zone 1 of the lake sediment core because diversity is typically highest in clear, slightly acidic, oligotrophic to mesotrophic waters (Stastny, 2009). The species diversity peaks within Zone 2 directly after the construction of the Dempster Highway (Figure 5.3). This spike in species diversity could be due to either the introduction of nutrients from the development of the Dempster Highway (such as Ca^{2+}, N or P), or an acceleration of regional temperatures that commenced between 1950 and 1970 (Thienpont et al., 2013).

Throughout Zone 1 and Zone 2 in lake sediment core FM02 (Figure 5.3), there are a few distinct trends that are indicative of regional warming. *Cosmarium* and *Euastrum* are both primarily benthic genera (Table 5.1), and therefore compete for nutrients and light close to the lake floor. Beginning in the ~AD 1800's, *Cosmarium* concentrations increase significantly, with maximum values around ~AD 1970 (Figure 5.3). At this time, *Euastrum* concentrations begin to decline significantly, aside from *E. psuedotuddalense*. *E. psuedotuddalense* favours mesotrophic conditions and is typically found in arctic-alpine regions (Coesel and Van Westen, 2013), but after extensive regional warming, this species also disappears (~AD 1995, ~2 cm) (Figure 5.3). The suspected cause for the shift in domination from *Euastrum* in Zone 1 to *Cosmarium* in Zone 2 is regional warming across the Northwest Territories at this time, although the influx of dust from the Dempster Highway construction could have enhanced this shift as well in the upper areas of the core (between 4 cm and 6 cm). *Euastrum* generally thrive in more acidic water bodies as well as in oligotrophic habitats (Coesel, 1982). Due to the slow division and favourable surface volume of *Euastrum*, it has the ability to thrive in oligotrophic conditions (Coesel, 1982). *Euastrum* also has the inability to adapt quickly to changes in the trophic level or to increases in pH, therefore making it difficult for this genus to continue dominating the lake ecosystem as nutrients and other elements are added from increased decomposition, from retrogressive thaw slumps in the surrounding catchment, or the influx of calcareous road dust. With the sensitivity of *Euastrum* to changes in pH and nutrient increases, *Cosmarium* can multiply and begin dominating lake FM02 in Zone 2, along with an increase in the concentration and species diversity of algal palynomorphs at this time. *Cosmarium* are well adapted to disturbance as they have a very short generation time (Coesel, 1982). Although they can be found at times in oligotrophic conditions (Coesel et al., 1978), many adapt well to shifts in the trophic level, such as from oligotrophic to eutrophic conditions and increases in conductivity (Coesel, 1982). *C. pyramidatum* (Figure 5.3), which shows a consistent increase since ~AD 1606, is a species that favours oligo-mesotrophic transitional zones (Stastny, 2009). This is indicative of increasing nutrient levels since the early AD 1600s in FM02. This species along with *E. psuedotuddalense* and *Pediastrum* spp, experienced a drastic change around 4 cm to 6 cm, which is likely attributed to the construction of the Dempster Highway. Lake FM02 is located only 50 m from the highway, at the bottom of a steep hill. During construction of the Dempster Highway, it is likely that the construction process would have produced loose road material and dust that could easily be washed from the highway corridor into Lake FM02. Changes in Ca^{2+}, N and P concentrations in lake FM02 at this time could have contributed to the large increase and later sharp decrease in *C. pyramidatum, E. pseudotuddalense* and *Pediastrum* spp. *Cosmarium* can also be generally indicative of warmer and more humid climate periods (Bera, 2004), so the continuous increase in this genus can be attributed to regional warming. It is quite clear that the decrease and later complete disappearance of *Euastrum* and the increasing dominance of *Cosmarium* could be due to the changes that the

Canadian Arctic climate has undergone in the last 150 years. It is also possible that regional warming ultimately masks the impacts of dust loading from the Dempster Highway on the algal palynomorph communities during recent decades.

The other trend that is visible between Zone 1 and Zone 2 is the shift from *Staurastrum* (Zone 1) to *Pediastrum* (Zone 2) (Figure 5.3). Both genera are generally planktonic and therefore are likely to compete for nutrients within the water column in lake FM02. It is evident that the appearance of *Pediastrum* spp. at ~AD 1800 (beginning of Zone 2) records significant change within lake FM02 as depicted by CONISS. *Pediastrum* spp. is mostly indicative of mesotrophic or eutrophic waters (Komarek and Jankovska, 2001; Jankovska and Komarek, 2000; Nielsen and Sorensen, 1992) (Table 5.1), so the introduction of this genus is likely due to increased nutrients from increased decomposition due to increasing lake water temperatures, or from increasing nutrients due to a possible increasing active layer thickness and thawing of permafrost in the surrounding catchment. When *Pediastrum* spp. is present in a lake, it can also be indicative of a shift to a warmer climate (Wolowski et al., 2002). *Staurastrum,* on the other hand, is usually found in oligotrophic lakes, although it can at times survive in eutrophic and alkaline lake environments (Coesel, 1982; Coesel et al., 1987). *Staurastrum* can survive in these eutrophic/alkaline conditions, but *Pediastrum* spp. is also a planktonic genus that favours mesotrophic to eutrophic lake waters. Lake FM02, through field observation and an in depth look at the water chemistry, would not be considered eutrophic, but more transitional or mesotrophic, therefore favouring *Pediastrum* spp. The *Pediastrum* spp. likely replaces *Staurastrum* after the AD 1800's, eventually causing *Staurastrum* to disappear completely. Evidence that suggests *Pediastrum* spp. replaces

Staurastrum is visible at ~AD 1982 (Figure 5.3), when *Pediastrum* spp. disappears momentarily, and *Staurastrum* concentrations rise to their highest concentration since ~AD 1700. The shift from a lake dominated by *Staurastrum* and *Euastrum* species to one dominated by *Pediastrum* spp. and *Cosmarium* species, is indicative of a shift to a warmer climate, more mesotrophic or transitional water conditions, and a more basic (pH) lake environment. Both the construction of the Dempster Highway and an increase in the rate of regional warming ~AD 1950/~AD 1970 suggested by Thienpont et al. (2013) could explain the sharp increase in *Cosmarium* and *Pediastrum*.

Aside from changes to the genera and species composition between Zone 1 and Zone 2, the species diversity also shows changes between zones and shows a brief shift around the construction of the Dempster Highway (Figure 5.4). At the division between Zone 1 and Zone 2 (~8 cm, ~AD 1894), there is a clear decrease in species diversity. At this time, temperatures were beginning to warm and the Little Ice Age had ended. It is clear that at this time there was a shift in the algal palynomorph assemblage of lake FM02, so a decrease in species diversity is not surprising. Although the temperatures at this time were likely beginning to rise, there were many changes going on within the lake that could have been cause for a decrease in species diversity. Around the time of the Dempster Highway construction, there is a large instantaneous increase in the species diversity (~4.5cm, ~AD 1958). This marked increase is suggested to be a result of added nutrients (such as Ca^{2+} and N) (Smith et al., 1999) from the dust along the Dempster Highway, along with increasing temperatures in the area during this time.

Some of the algal palynomorph assemblages are indicative of increases in conductivity and pH, which would suggest the addition of calcareous road dust, but many

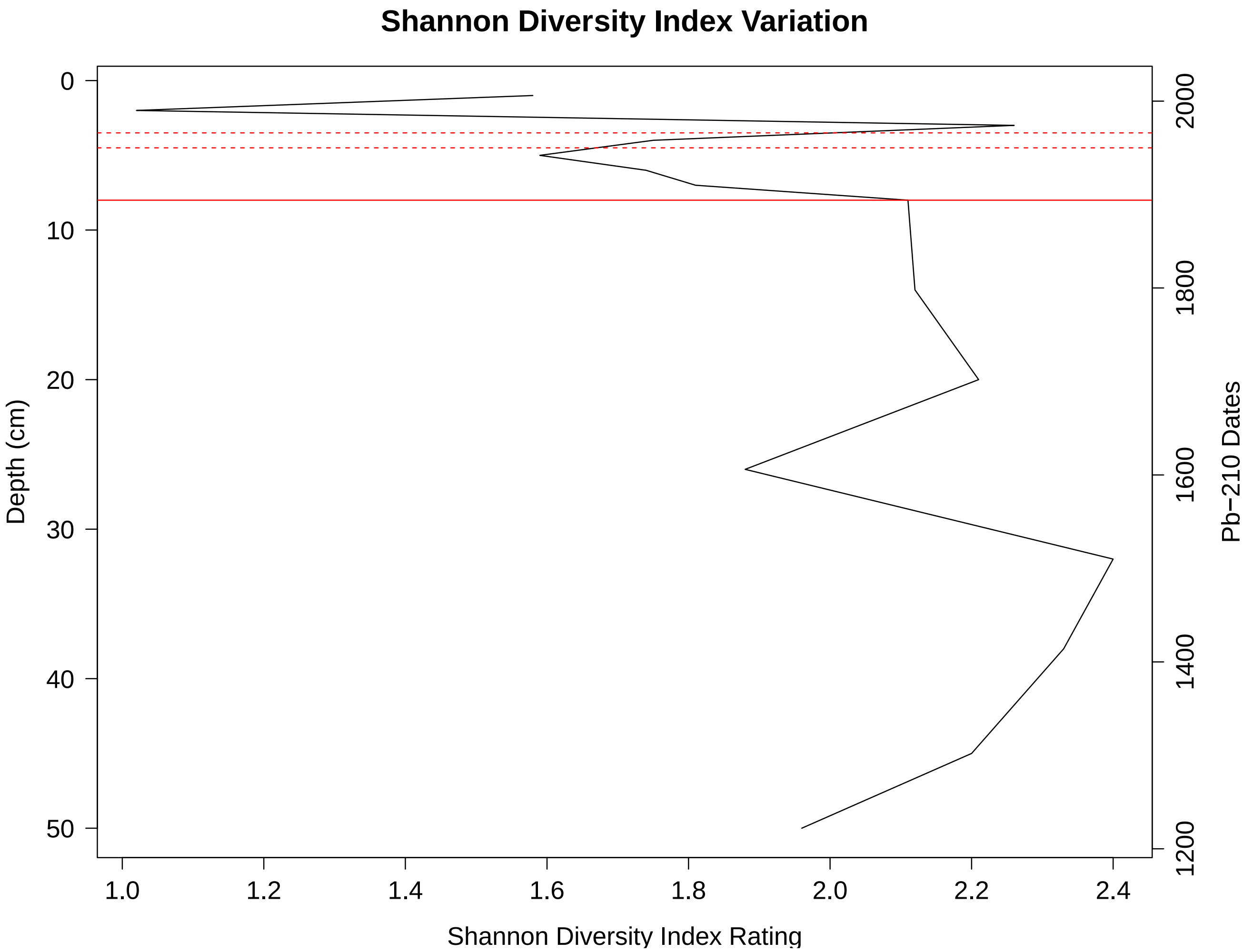

Figure 5.4 The Shannon Diversity Index Variation throughout the impacted core, FM02. The index spikes around the construction of the Dempster Highway but later decreases after the construction period. The solid red line depicts the separation between Zone 1 and Zone 2 as determined by CONISS, while the dotted red lines portray the approximate construction period of the Dempster Highway (between 3.5 and 4.5 cm) Analysis completed by Caitlin Garner (C. Garner, unpublished data).

of these changes begin before the construction of the Dempster Highway. Dust deposition is likely more instantaneous, affecting the water chemistry in some lakes directly, and possibly the algal palynomorphs during construction, but the highway does not appear to have a prolonged impact that is visible within the sediment record, and it is unknown at this time if there is a prolonged impact on the algal palynomorph communities. Also, without historical water chemistry data, it is difficult to interpret what the conductivity or pH levels were like in FM02, prior to highway construction. If lake FM02 had a generally higher conductivity and or pH, than additions of calcareous road dust may not have increased levels enough to reach a threshold response from the algal palynomorph community once construction of the highway was completed.The lack of increase in K^{+}, Ti^{3+}, Tb^{3+}, and Sr^{2+} in the physical sedimentology within the impacted cores (FM02 and FM04) also suggests that the impacts of the construction of the Dempster Highway, and subsequent production of road dust, do not show up in the sediment history. Changes to these elements are likely seasonal or yearly rather than abrupt changes due to Dempster Highway construction. The shift from a *Euastrum* spp. and *Staurastrum* spp. dominated lake with a moderate species diversity, to a *Cosmarium* spp. and *Pediastrum* spp. (Figure 5.3) dominated lake, with a much larger species diversity (Figure 5.4), suggests that either a warming response (Thienpont et al., 2013) or dust from the construction of the Dempster Highway could be the main cause for the changes within the algal palynomorph community. With knowledge of the timing of regional warming in the area along with the timing of the changes in algal palynomorph assemblages and the construction of the Dempster Highway, lack of evidence in elemental variations, and evidence that suggests some lakes close to the Dempster Highway show increases in specific physical water chemistry, major ions and Sr^{2+}; a strong case is made that these changes are due to the combination of regional climate warming and dust loading from the Dempster Highway.

Chapter 6

Conclusion

6.1 Conclusions of Study Findings

Current research indicates that dust from gravel highways, such as the Dalton Highway, Alaska, and the Dempster Highway, NWT, can have negative impacts on roadside vegetation and nearby permafrost temperature regimes. Although the impacts of road dust from Arctic gravel highways have been well documented for terrestrial ecosystems, the impacts on aquatic ecosystems are not well known. This study used algal palynomorphs, water chemistry measurements and physical sedimentology to determine the impact that calcareous road dust from the Dempster Highway may have on Arctic aquatic ecosystems. The lack of research on the impacts of dust loading on aquatic ecosystems limits the capacity for informed regulatory decisions in regards to future development within the Canadian Arctic. The three main objectives of this thesis were: (1) to determine if dust loading from the Dempster Highway alters the water chemistry (i.e. pH, conductivity, concentration of major ions) in lakes within close proximity to the Dempster Highway, (2) to establish whether or not heavy metals and other elemental concentrations changed after the construction of the Dempster Highway, and (3) to determine if the construction of the Dempster Highway impacted communities of algal palynomorphs adjacent to the Dempster Highway (FM02).

In simple comparison, the water chemistry results indicated that dust loading from the Dempster Highway could have an impact on aquatic ecosystems within a close proximity to the highway. Lakes within 1 km of the Dempster Highway generally had higher values for alkalinity, conductivity, TDS, pH, Ca^{2+}, Mg^{2+}, hardness, NO_3-N,

NO_2+NO_3-N, SO_4^{2-} and Sr^{2+}. Active retrogressive thaw slumps on lake shorelines also had impacts on lakes up to 20 km away from the Dempster Highway. Although many lakes within 1 km had much higher values for these variables, lake FM10 (50 m from the highway), FM05 (430 m from the highway), FM04 (670 m from the highway) and FM15 (730 m from the highway) had values that closely resembled those of lakes between ~5 km and 30 km away from the Dempster Highway. It is not clear at this time why these lakes exhibited much lower values when compared to other lakes within 1 km of the highway. Possible factors include, but are not limited to, the possible influx of groundwater to some lakes, possible increased evaporation in certain lakes, increased surface roughness due to tall shrub growth on the sides of the highway that may capture some of the dust loading before it reaches the lakes, and it is possible that dust may not reach these lakes as they are several meters from the highway or that the dust does not make it to these lakes often enough throughout the year.

Based on the elemental profiles of K^{+}, Ti^{3+}, Fe^{2+}, Tb^{3+}, Sr^{2+} and Ca^{2+} in lakes FM02, FM04 and FM06, it appears that the construction of the Dempster Highway did not produce a reliable elemental signal within the sediment record. These elements were found to be most prominent within the gravel sample from the Dempster Highway, but their presence in the sediment cores from lakes FM02 and FM04 show no changes at the time of construction for the Dempster Highway. It is unclear why the elemental signature within the sediment record was unaffected by the construction of the Dempster Highway. One possible reason is the lack of dust loading within lakes FM02 and FM04. From the water chemistry, FM04 was unique to most of the other lakes within 1 km of the Dempster Highway, with most variables recording lower concentrations. It could be that a smaller amount of road dust is reaching the lake, as it is relatively far (670 m) away from the Dempster Highway. In lake FM02, it could be that there is not a constant supply of road dust. The dust may have a large impact directly on the water chemistry or algal palynomorphs as it enters the lake, however, there seems to be no record of the Dempster Highway within the lake sediment core.

The algal palynomorph communities were predicted to respond to changes in water chemistry and water quality around the construction of the Dempster Highway. Analyses of algal palynomorph assemblages determined that FM02, one of the potentially impacted lakes, showed some response to the addition of road dust during construction. The evidence of impact was the brief increase in species diversity around the time of highway construction, as well as the sharp increases and later decreases in *C. pyramidatum, E. pseudotuddalense* and *Pediastrum* spp. At the same time, it is possible that regional climate warming is masking the impacts that are associated with dust loading on the algal palynomorph communities in FM02 after the construction period. Warmer temperatures and increased precipitation could cause the occurrence of retrogressive thaw slumps to increase across the Peel Plateau (Kokelj et al., 2013; Malone et al., 2013; Thienpont et al., 2013; Kokelj et al., 2005), which induces sediment transport and the influx of nutrients and elements such as Ca^{2+}, Mg^{2+} and SO_4^{2-} into surrounding lakes. Along with this, increasing lake water temperatures induce increased decomposition in the lakes and therefore more nutrients are available to genera such as *Pediastrum* and *Cosmarium,* which can flourish, which was experienced in lake FM02. The shift from oligotrophic and acidic conditions which are favourable to those algal palynomorph genera that prefer mesotrophic/eutrophic conditions and that are less sensitive to changes in both nutrient amounts and conductivity/pH, suggests that regional warming is having an impact on the algal palynomorph communities in lake FM02, while the construction of the Dempster Highway likely had a short-lived impact between 4 cm and 6 cm.

Although the algal palynomorph communities only seem to be affected by the initial construction of the Dempster Highway, other aquatic biota could show changes if they are more sensitive to changes in the water chemistry and potentially less to changes in lake temperature. The results shown here do not indicate that other types of biota within the aquatic ecosystems along the Dempster Highway are or are not affected by dust loading. However, the results do indicate that warming across the Canadian Arctic could be leading to changes to the aquatic environments through increasing retrogressive thaw slump activity and overall increases in lake water temperatures. Continuous monitoring of lakes in this region is important in order to understand impacts of both the Dempster Highway construction/maintenance and climate change.

6.2 Recommendations for Future Work

It is recommended that future studies investigate further the impacts of calcareous road dust on the aquatic environments, along with continuous monitoring of the terrestrial environments, to gain a better understanding about how road dust effects the Arctic system. It is important to identify the effects of road dust on the terrestrial environment and subsequent interactions with aquatic environments. Some impacts from calcareous road dust deposition might not be the direct input of dust to the lakes, but could be more in depth such as the changes in vegetation due to road dust and how this can affect the types of biota found in surrounding lakes. For example, *Sphagnum* has been known to decrease extensively at the edges of gravel highways as the calcareous road dust increases the pH of the soil and since *Sphagnum* are quite sensitive to changes in pH, they are easily replaced with tall shrubs. It would be interesting to investigate the relationship between *Sphagnum* and algal palynomorphs (such as *Pediastrum*, which is epiphytic) found within the lakes close to the Dempster Highway. The impact on the ecosystem from the shift of *Sphagnum* to tall shrubs is unknown and could be explored further.

It would also be beneficial to put dust traps alongside the Dempster Highway at varying distances away, in order to gain a better understanding of how the dust moves and where the dust is accumulating the most. The dust traps would be a great indicator of where the dust loading is greatest. Based on those findings, lakes in those areas could be targeted for sampling to try and identify the effects of the road dust on the aquatic ecosystems. Like dust traps, snow samples can also be good indicators of how the dust is travelling away from the road. If snow samples were taken for a number of consecutive years, they could also help determine how much and how far dust is transported during the cold season and under different meteorological conditions, such as a year with greater snowfall versus a year with less snowfall.

Although there was no statistical difference in the multitude of environmental parameters examined in this study for lakes located north and south of the Dempster Highway, this should be investigated further along with the dust traps and meteorological measurements (wind specifically). This could help us gain a better understanding of how water chemistry varies with increasing distance from the Dempster Highway, how water chemistry varies between lakes north and south of the highway, as well as how wind may influence dust loading in lakes surrounding gravel highways.

Since the 2015 cores were only sectioned at 1 cm intervals, it would be beneficial to do a more in-depth sub-sampling protocol, possibly down to 0.25 cm intervals, in order to pick up the direct impacts of the Dempster Highway dust loading in cores within a close proximity to the highway within the algal palynomorph community. Higher resolution sampling and processing could potentially discover new signals within the algal palynomorphs and could better depict the impacts of climate warming within the Canadian Arctic. Also, completing algal palynomorph counts such as this for lakes at varying distances from the Dempster Highway would aid in determining whether the trends are in fact climate related (if they are the same across all cores) or if they are due to anthropogenic changes such as the construction of the Dempster Highway.

The catchment characteristics are very important to small lakes and ponds, so understanding these characteristics can be helpful when investigating impacts from road dust and climate change. These types of characteristics can be examined using remotely sensed imagery, which would help indicate different types of vegetation. A digital elevation model (DEM) would also be beneficial as it would give a general idea of the elevation differences between lakes and the Dempster Highway. Elevation plays a key role in dust deposition as well as the addition of nutrients and other elements from the surrounding environment, so a DEM would be beneficial. There could be a division in the lakes by a catchment characteristic, but at this time, it might look as though the Dempster Highway is having an impact on these same lakes; determining these characteristics could help to further investigate lakes surrounding the Dempster Highway.

As this research is some of the first to look at the aquatic ecosystems along the

Dempster Highway and how they are impacted by calcareous road dust, there is still plenty of research to be completed surrounding the Dempster Highway and the newly built Tuktoyaktuk Highway.

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Appendices

Appendix I

Raw Water Chemistry Data From Taiga Environmental Laboratory

i) Nutrients data collected at all 28 sample lakes. Variables include NH_3-N, total nitrogen (TN), dissolved organic carbon (DOC) and total organic carbon (TOC).

Distance (km)	Site	Latitude	Longitude	NH_3-N	TN	DOC	TOC
0.04	FM-03*	67 15'30.6"	135 6'48.26"	0.01	0.40	9.90	10.30
0.05	FM-02	67 14'30.49"	135 19'34.77"	0.01	0.46	6.30	7.00
0.05	FM-10	67 16'8.25"	135 3'52.26"	0.01	0.66	12.40	14.00
0.06	FM-50	67°15'7.94"	135° 7'46.27"	0.01	0.48	14.70	15.80
0.21	FM-17	67 12'30.68"	135 37'29.78"	0.04	0.37	8.00	8.80
0.24	FM-11	67 14'38.95"	135 11'16.89"	0.01	0.49	15.70	16.10
0.43	FM-12	67 13'3.62'	135 27'21.25"	0.01	0.43	13.70	15.00
0.43	FM-05	67 14'39.00"	135 20'23.29"	0.01	0.38	7.00	9.70
0.57	FM-14*	67 15'12.99"	135 11'36.09"	0.01	0.36	11.20	12.30
0.64	DEMP LK 1*	67 15'9.46"	135 12'5.04"	0.01	0.25	6.60	6.50
0.67	FM-04	67 15'7.06"	135 5'57.31"	0.01	0.44	12.40	14.80
0.73	FM-15	67 13'31.86"	135 30'10.79"	0.01	0.39	13.40	17.50
0.79	DEMP LK 2*	67 15'9.55"	135 12'25.72"	0.01	0.31	9.30	9.90
0.93	FM-16	67 15'26.20"	135 9'15.79"	0.01	0.54	14.40	16.60
0.95	FM-18	67 13'25.30"	135 34'57.88"	0.39	1.41	15.20	17.00
4.82	FM-19	67 10'30.79"	135 29'35.36"	0.01	0.45	15.00	17.00
5.48	DEMP LK 3	67 17'5.09"	135 24'0.64'	0.01	0.45	13.60	15.20
5.77	FM-20	67 11'32.88"	135 8'56.10"	0.01	0.81	13.30	16.60
5.86	DEMP LK 4	67 17'25.85"	135 22'53.96"	0.01	0.56	15.50	17.70
7.66	FM-27	67 18'32.22"	135 13'39.74"	0.01	0.48	14.00	17.20
8.12	FM-21	67 9'48.76"	135 21'21.04'	0.01	0.56	17.50	19.90
15.68	FM-23	67 5'57.17"	135 12'2.85"	0.01	0.37	13.10	14.10
16.72	FM-30	67 23'21.50"	135 18'14.30"	0.01	0.42	11.90	13.10
18.47	FM-29*	67 23'53.18"	135 25'32.69"	0.01	0.21	5.60	5.60
18.92	FM-28	67 23'11.17"	135 32'56.08"	0.01	0.51	12.30	15.00
18.93	FM-24	67 4'3.98"	135 21'41.66"	0.01	0.41	12.20	16.40
23.62	FM-06	67 30'20.23"	135 18'35.33"	0.01	0.46	14.20	15.50
29.87	FM-31	67 30'4.01"	135 21'59.31"	0.01	0.32	8.20	8.90

ii) Physical Parameters Collected at all 28 Sample Lakes. Physicals include total phosphorus (TP), alkalinity (Alkal), conductivity (Cond), total dissolved solids (TDS), total suspended solids (TSS), turbidity (Turb) and pH. Site names marked with an asterisk are lakes where a slump is present on one of its edges or where a retrogressive thaw slump is within the catchment.

Distance (km)	Site	Latitude	Longitude	TP	Alkal	Cond	TDS	TSS	Turb	pH
0.04	FM-03*	67 15'30.6"	135 6'48.26"	0.02	74.60	432.00	337.00	3.00	0.76	8.02
0.05	FM-02	67 14'30.49"	135 19'34.77"	0.03	22.60	141.00	117.00	13.00	3.67	7.43
0.05	FM-10	67 16'8.25"	135 3'52.26"	0.13	4.90	26.90	47.00	4.00	3.69	6.58
0.06	FM-50	67°15'7.94"	135° 7'46.27"	0.02	65.40	565.00	398.00	4.00	1.88	7.89
0.21	FM-17	67 12'30.68"	135 37'29.78"	0.03	49.80	334.00	227.00	4.00	3.22	7.51
0.24	FM-11	67 14'38.95"	135 11'16.89"	0.01	29.30	227.00	168.00	3.00	1.02	7.59
0.43	FM-12	67 13'3.62'	135 27'21.25"	0.01	20.20	101.00	93.00	10.00	1.06	7.26
0.43	FM-05	67 14'39.00"	135 20'23.29"	0.03	0.60	10.40	25.00	3.00	2.93	5.63
0.57	FM-14*	67 15'12.99"	135 11'36.09"	0.01	11.60	106.00	91.00	3.00	2.18	7.14
0.64	DEMP LK 1*	67 15'9.46"	135 12'5.04"	0.01	121.00	620.00	430.00	3.00	0.93	8.14
0.67	FM-04	67 15'7.06"	135 5'57.31"	0.05	2.50	33.80	66.00	3.00	3.60	6.14
0.73	FM-15	67 13'31.86"	135 30'10.79"	0.02	1.10	13.60	48.00	3.00	1.14	5.53
0.79	DEMP LK 2*	67 15'9.55"	135 12'25.72"	0.01	86.90	257.00	171.00	3.00	0.32	8.06
0.93	FM-16	67 15'26.20"	135 9'15.79"	0.04	8.60	124.00	115.00	7.00	9.43	6.77
0.95	FM-18	67 13'25.30"	135 34'57.88"	0.15	22.30	118.00	114.00	3.00	21.30	7.23
4.82	FM-19	67 10'30.79"	135 29'35.36"	0.02	7.00	30.50	51.00	4.00	4.25	6.66
5.48	DEMP LK 3	67 17'5.09"	135 24'0.64'	0.05	2.50	15.40	50.00	3.00	2.81	6.32
5.77	FM-20	67 11'32.88"	135 8'56.10"	0.09	3.30	46.60	60.00	7.00	8.55	6.46
5.86	DEMP LK 4	67 17'25.85"	135 22'53.96"	0.07	9.30	34.00	67.00	3.00	4.90	6.93
7.66	FM-27	67 18'32.22"	135 13'39.74"	0.03	2.30	23.60	50.00	3.00	2.70	6.11
8.12	FM-21	67 9'48.76"	135 21'21.04'	0.02	6.10	21.90	52.00	3.00	1.84	6.58
15.68	FM-23	67 5'57.17"	135 12'2.85"	0.02	7.90	39.60	55.00	3.00	2.20	6.92
16.72	FM-30	67 23'21.50"	135 18'14.30"	0.02	9.20	52.40	51.00	3.00	0.85	7.07
18.47	FM-29*	67 23'53.18"	135 25'32.69"	0.00	4.30	439.00	292.00	3.00	0.82	6.79

ii) Physicals continued. Vairables include total phosphorus (TP), alkalinity (Alkal), conductivity (Cond), total dissolved solids (TDS), total suspended solids (TSS), turbidity (Turb) and pH.

Distance (km)	Site	Latitude	Longitude	TP	Alkal	Cond	TDS	TSS	Turb	pH
18.92	FM-28	67 23'11.17"	135 32'56.08"	0.04	2.10	15.80	44.00	3.00	4.00	6.08
18.93	FM-24	67 4'3.98"	135 21'41.66"	0.04	0.60	13.50	42.00	3.00	3.13	5.31
23.62	FM-06	67 30'20.23"	135 18'35.33"	0.02	3.70	16.70	43.00	5.00	2.00	6.42
29.87	FM-31	67 30'4.01"	135 21'59.31"	0.01	16.90	84.00	70.00	3.00	1.63	7.36

iii) Major Ions Collected at all 28 Sample Lakes. Variables include: calcium (Ca), chloride (Cl^-), fluoride (F^-), hardness, magnesium (Mg), nitrate as nitrogen (NO_3-N), nitrate/nitrite as nitrogen (NO_3/NO_2-N), nitrite as nitrogen (NO_2-N), potassium (K), silica (reactive) (Si), sodium (Na) and sulphate (SO_4). Lake sites marked with asterisks have a slump on one edge or a slump within their catchment.

Distance (km)	Site	Latitude	Longitude	Ca	Cl^-	F^-	Hardness	Mg	NO_3-N	NO_3/NO_2-N	NO_2-N	K	Si	Na	SO_4
0.04	FM-03*	67 15'30.6"	135 6'48.26"	48.60	0.70	0.10	207.00	20.80	0.11	0.12	0.01	1.20	0.19	12.30	155.00
0.05	FM-02	67 14'30.49"	135 19'34.77"	12.60	1.00	0.10	61.50	7.30	0.05	0.06	0.01	0.40	0.57	3.90	45.00
0.05	FM-10	67 16'8.25"	135 3'52.26"	3.30	0.70	0.10	12.10	0.90	0.03	0.03	0.01	0.30	1.71	0.70	5.00
0.06	FM-50	67°15'7.94"	135° 7'46.27"	66.50	0.70	0.10	274.00	26.30	0.06	0.07	0.01	0.70	1.20	15.80	234.00
0.21	FM-17	67 12'30.68"	135 37'29.78"	34.5	0.7	0.1	159	17.8	0.1	0.11	0.01	1	3.86	7.9	125
0.24	FM-11	67 14'38.95"	135 11'16.89"	28.5	0.7	0.1	111	9.6	0.05	0.06	0.01	0.2	1.56	4	85
0.43	FM-12	67 13'3.62'	135 27'21.25"	12.1	0.7	0.1	47.6	4.2	0.04	0.05	0.01	0.3	0.647	1.8	28
0.43	FM-05	67 14'39.00"	135 20'23.29"	1	0.7	0.1	4.6	0.5	0.02	0.02	0.01	0.3	0.74	0.3	2
0.57	FM-14*	67 15'12.99"	135 11'36.09"	12.5	0.7	0.1	46.6	3.8	0.03	0.04	0.01	0.6	2.03	2.1	35
0.64	DEMP LK 1*	67 15'9.46"	135 12'5.04"	96.4	0.7	0.1	338	23.5	0.14	0.15	0.01	2.1	0.715	6.7	226
0.67	FM-04	67 15'7.06"	135 5'57.31"	4	0.7	0.1	15	1.2	0.02	0.02	0.01	0.2	1.52	0.6	9
0.73	FM-15	67 13'31.86"	135 30'10.79"	1.9	0.7	0.1	8	0.8	0.02	0.02	0.01	0.1	4.99	0.3	1
0.79	DEMP LK 2*	67 15'9.55"	135 12'25.72"	43	0.7	0.1	129	5.2	0.1	0.12	0.01	0.3	1.37	0.5	42

iii) Major ions continued. Variables include: calcium (Ca), chloride (Cl^-), fluoride (F^-), hardness, magnesium (Mg), nitrate as nitrogen (NO_3-N), nitrate/nitrite as nitrogen (NO_3/NO_2-N), nitrite as nitrogen (NO_2-N), potassium (K), silica (reactive) (Si), sodium (Na) and sulphate (SO_4). Lake sites marked with asterisks have a slump on one edge or a slump within their catchment.

Distance (km)	Site	Latitude	Longitude	Ca	Cl^-	F^-	Hardness	Mg	NO_3-N	NO_3/NO_2-N	NO_2-N	K	Si	Na	SO_4
0.95	FM-18	67 13'25.30"	135 34'57.88"	12.3	0.7	0.2	53.4	5.5	0.09	0.1	0.01	0.9	2.6	0.9	32
4.82	FM-19	67 10'30.79"	135 29'35.36"	4.4	0.7	0.1	16	1.2	0.02	0.02	0.01	0.2	2.67	0.3	4
5.48	DEMP LK 3	67 17'5.09"	135 24'0.64'	2.4	0.7	0.1	8.9	0.7	0.02	0.02	0.01	0.2	1.97	0.2	1
5.77	FM-20	67 11'32.88"	135 8'56.10"	4.3	0.7	0.1	17.8	1.7	0.03	0.03	0.01	0.4	1.03	1.5	14
5.86	DEMP LK 4	67 17'25.85"	135 22'53.96"	5	0.7	0.1	18.1	1.4	0.02	0.03	0.01	0.3	1.93	0.3	3
7.66	FM-27	67 18'32.22"	135 13'39.74"	2.4	0.7	0.1	10.2	1	0.02	0.02	0.01	0.3	1.4	0.3	4
8.12	FM-21	67 9'48.76"	135 21'21.04'	3.4	0.7	0.1	11.6	0.8	0.03	0.03	0.01	0.1	0.346	0.3	1
15.68	FM-23	67 5'57.17"	135 12'2.85"	4.5	0.7	0.1	18.4	1.8	0.03	0.03	0.01	0.4	2.7	0.6	7
16.72	FM-30	67 23'21.50"	135 18'14.30"	6.4	0.7	0.1	24.3	2.1	0.03	0.03	0.01	0.2	0.279	0.8	13
18.47	FM-29*	67 23'53.18"	135 25'32.69"	31.2	0.7	0.4	139	14.9	0.08	0.09	0.01	1.9	0.549	NA	207
18.92	FM-28	67 23'11.17"	135 32'56.08"	1.5	0.7	0.1	7.1	0.8	0.02	0.03	0.01	0.3	1.33	0.4	2
18.93	FM-24	67 4'3.98"	135 21'41.66"	1.5	0.7	0.1	6.2	0.6	0.02	0.02	0.01	0.1	2.78	0.3	2
23.62	FM-06	67 30'20.23"	135 18'35.33"	2.2	0.7	0.1	8.6	0.8	0.02	0.03	0.01	0.4	0.855	0.2	1
29.87	FM-31	67 30'4.01"	135 21'59.31"	10.2	0.7	0.1	39.1	3.3	0.05	0.06	0.01	0.6	1.11	0.6	20

iv) Metals Collected at all 28 Sample Lakes. The variables included here are: aluminum (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), cesium (Cs), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb) and lithium (Li).

Distance (km)	Site	Latitude	Longitude	Al	Sb	As	Ba	Be	Cd	Cs	Cr	Co	Cu	Fe	Pb	Li
0.04	FM-03*	67 15'30.6"	135 6'48.26"	10.20	0.30	0.60	49.10	0.10	0.10	0.10	0.10	0.10	8.90	54.00	0.10	19.50
0.05	FM-02	67 14'30.49"	135 19'34.77"	43.80	0.40	0.50	42.20	0.10	0.10	0.10	0.20	0.10	10.90	235.00	0.10	3.50
0.05	FM-10	67 16'8.25"	135 3'52.26"	232.00	0.50	2.00	59.00	0.10	0.10	0.10	0.80	0.80	11.50	2680.00	0.50	2.20
0.06	FM-50	67°15'7.94"	135° 7'46.27"	51.00	0.30	0.60	51.50	0.10	0.20	0.10	0.30	0.30	7.70	232.00	0.10	25.30
0.21	FM-17	67 12'30.68"	135 37'29.78"	75.40	0.40	0.70	54.40	0.10	0.10	0.10	0.30	0.50	9.60	596.00	0.10	13.70
0.24	FM-11	67 14'38.95"	135 11'16.89"	34.70	0.30	0.60	49.90	0.10	0.10	0.10	0.30	0.10	10.60	232.00	0.10	4.70
0.43	FM-12	67 13'3.62"	135 27'21.25"	65.50	0.40	0.40	58.10	0.10	0.10	0.10	0.40	0.20	5.60	256.00	0.10	3.40
0.43	FM-05	67 14'39.00"	135 20'23.29"	199.00	0.50	0.50	22.70	0.10	0.10	0.10	0.70	1.00	9.00	640.00	0.10	2.00
0.57	FM-14*	67 15'12.99"	135 11'36.09"	64.70	0.40	0.60	40.10	0.10	0.10	0.10	0.30	0.10	8.20	208.00	0.10	4.10
0.64	DEMP LK 1*	67 15'9.46"	135 12'5.04"	29.60	0.30	0.80	39.50	0.10	0.10	0.10	0.10	0.10	7.80	36.00	0.10	17.00
0.67	FM-04	67 15'7.06"	135 5'57.31"	226.00	0.40	0.90	36.30	0.10	0.10	0.10	0.60	0.80	9.40	1400.00	0.20	2.10
0.73	FM-15	67 13'31.86"	135 30'10.79"	226.00	0.40	0.40	37.30	0.10	0.10	0.10	1.00	2.00	6.30	881.00	0.10	3.10
0.79	DEMP LK 2*	67 15'9.55"	135 12'25.72"	5.70	0.30	0.50	60.90	0.10	0.20	0.10	0.10	0.10	7.20	21.00	0.10	2.30
0.93	FM-16	67 15'26.20"	135 9'15.79"	254.00	0.50	1.50	59.80	0.10	0.20	0.10	0.80	2.90	10.20	1930.00	0.30	5.50
0.95	FM-18	67 13'25.30"	135 34'57.88"	256.00	0.50	3.50	60.50	0.10	0.20	0.10	0.90	2.10	10.30	4920.00	0.50	8.40
4.82	FM-19	67 10'30.79"	135 29'35.36"	203.00	0.40	0.90	54.60	0.10	0.20	0.10	0.80	0.80	13.10	1310.00	0.70	2.40
5.48	DEMP LK 3	67 17'5.09"	135 24'0.64"	216.00	0.40	0.80	30.30	0.10	0.10	0.10	0.70	0.40	6.40	1710.00	0.20	1.60
5.77	FM-20	67 11'32.88"	135 8'56.10"	315.00	0.40	1.10	71.70	0.10	0.10	0.10	0.90	0.50	8.10	2580.00	0.60	2.80
5.86	DEMP LK 4	67 17'25.85"	135 22'53.96"	216.00	0.40	2.20	61.20	0.10	0.20	0.10	0.70	0.50	9.10	1970.00	0.30	2.10
7.66	FM-27	67 18'32.22"	135 13'39.74"	181.00	0.40	0.60	48.60	0.10	0.10	0.10	0.80	0.50	6.60	1190.00	0.20	2.80
8.12	FM-21	67 9'48.76"	135 21'21.04"	132.00	0.40	0.50	22.60	0.10	0.10	0.10	0.40	0.60	6.70	1110.00	0.10	0.90
15.68	FM-23	67 5'57.17"	135 12'2.85"	111.00	0.40	0.80	45.90	0.10	0.10	0.10	0.50	0.10	9.50	659.00	0.10	2.70
16.72	FM-30	67 23'21.50"	135 18'14.30"	51.20	0.40	0.40	36.50	0.10	0.20	0.10	0.40	0.10	7.00	409.00	0.10	2.10
18.47	FM-29*	67 23'53.18"	135 25'32.69"	40.30	0.40	0.20	28.10	0.10	0.10	0.10	0.10	0.20	4.20	95.00	0.10	32.80

iv) Metals continued. The variables included are: aluminum (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), cesium (Cs), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb) and lithium (Li).

Distance (km)	Site	Latitude	Longitude	Al	Sb	As	Ba	Be	Cd	Cs	Cr	Co	Cu	Fe	Pb	Li
18.92	FM-28	67 23'11.17"	135 32'56.08"	262.00	0.50	1.00	44.20	0.10	0.20	0.10	0.90	0.50	8.00	1260.00	0.30	1.80
18.93	FM-24	67 4'3.98"	135 21'41.66"	312.00	0.30	0.70	49.90	0.10	0.20	0.10	0.90	1.80	9.00	1370.00	0.10	2.30
23.62	FM-06	67 30'20.23"	135 18'35.33"	125.00	0.40	0.90	29.10	0.10	0.10	0.10	0.40	0.20	9.20	997.00	0.10	1.10
29.87	FM-31	67 30'4.01"	135 21'59.31"	36.90	0.40	0.40	62.60	0.10	0.20	0.10	0.20	0.10	7.10	144.00	0.10	4.50

iv) Metals continued. The variables here include: manganese (Mn), molybdenum (Mo), nickel (Ni), rubidium (Rb), selenium (Se), silver (Ag), strontium (Sr), thallium (Tl), titanium (Ti), uranium (U), vanadium (V) and zinc (Zn).

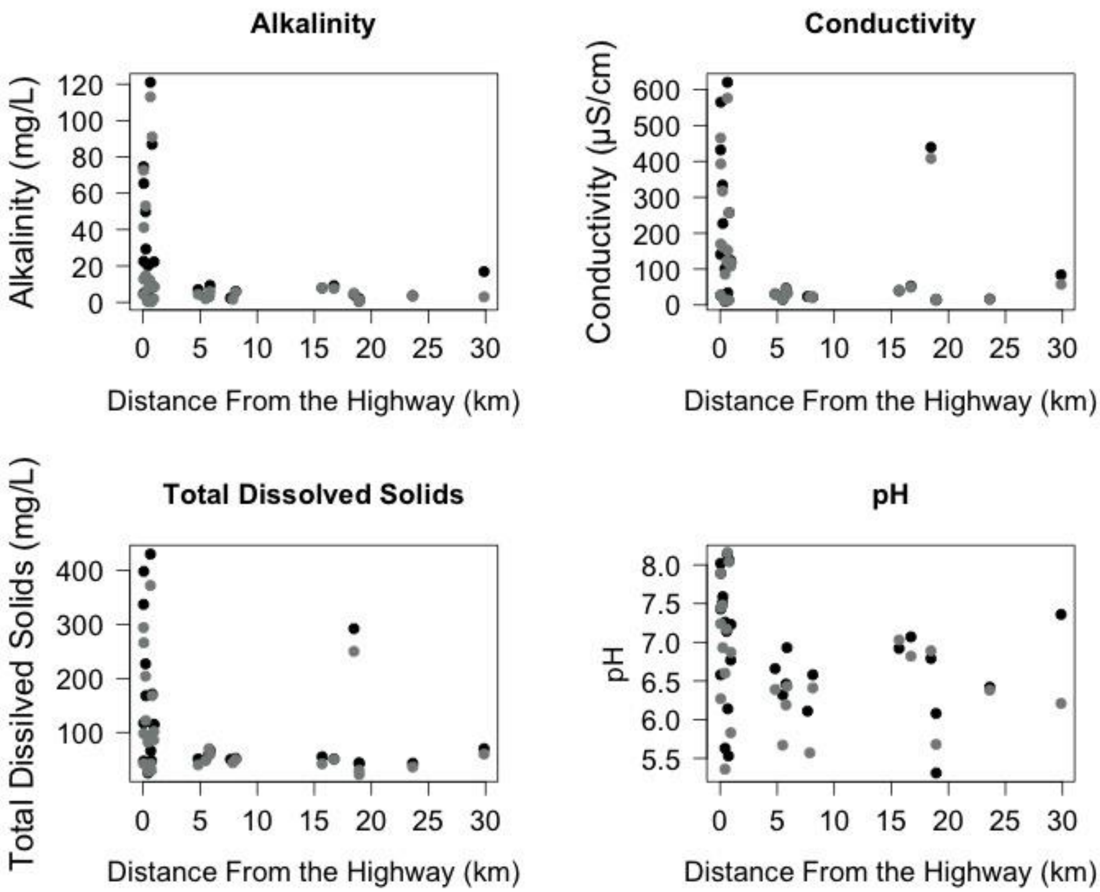
Distance (km)	Site	Latitude	Longitude	Mn	Mo	Ni	Rb	Se	Ag	Sr	Tl	Ti	U	V	Zn
0.04	FM-03*	67 15'30.6"	135 6'48.26"	17.80	0.30	1.10	0.70	0.50	0.10	118.00	0.10	0.10	0.10	0.10	5.00
0.05	FM-02	67 14'30.49"	135 19'34.77"	26.00	0.20	1.70	0.30	0.50	0.10	34.90	0.10	0.30	0.10	0.20	5.00
0.05	FM-10	67 16'8.25"	135 3'52.26"	30.80	0.20	4.40	0.50	0.50	0.10	13.90	0.10	1.50	0.10	1.50	11.60
0.06	FM-50	67°15'7.94"	135° 7'46.27"	12.20	0.30	5.30	0.40	0.50	0.10	151.00	0.10	0.40	0.10	0.20	5.00
0.21	FM-17	67 12'30.68"	135 37'29.78"	220.00	0.20	6.30	0.70	0.50	0.10	167.00	0.10	0.60	0.10	0.20	7.10
0.24	FM-11	67 14'38.95"	135 11'16.89"	7.30	0.20	3.50	0.20	0.50	0.10	66.20	0.10	0.40	0.10	0.10	5.00
0.43	FM-12	67 13'3.62"	135 27'21.25"	11.50	0.20	4.40	0.30	0.50	0.10	41.10	0.10	0.30	0.10	0.10	12.20
0.43	FM-05	67 14'39.00"	135 20'23.29"	20.30	0.10	3.60	0.40	0.50	0.10	4.80	0.10	1.10	0.10	0.80	8.30
0.57	FM-14*	67 15'12.99"	135 11'36.09"	13.40	0.20	3.60	0.50	0.50	0.10	31.40	0.10	0.40	0.10	0.20	6.20
0.64	DEMP LK 1*	67 15'9.46"	135 12'5.04"	4.30	0.50	1.10	1.10	0.50	0.10	275.00	0.10	0.40	0.30	0.20	5.30
0.67	FM-04	67 15'7.06"	135 5'57.31"	28.40	0.10	3.80	0.50	0.50	0.10	14.50	0.10	0.90	0.10	0.80	11.00
0.73	FM-15	67 13'31.86"	135 30'10.79"	35.60	0.10	4.90	0.10	0.50	0.10	8.50	0.10	0.50	0.10	0.30	10.90
0.79	DEMP LK 2*	67 15'9.55"	135 12'25.72"	2.30	0.20	0.40	0.30	0.50	0.10	92.10	0.10	0.20	0.10	0.10	5.00
0.93	FM-16	67 15'26.20"	135 9'15.79"	162.00	0.60	10.30	0.70	0.50	0.10	41.20	0.10	1.40	0.10	1.00	19.10
0.95	FM-18	67 13'25.30"	135 34'57.88"	196.00	1.00	9.30	1.50	0.50	0.10	58.90	0.10	1.90	0.10	2.50	9.90

iv) Metals continued. The variables here include: manganese (Mn), molybdenum (Mo), nickel (Ni), rubidium (Rb), selenium (Se), silver (Ag), strontium (Sr), thallium (Tl), titanium (Ti), uranium (U), vanadium (V) and zinc (Zn).

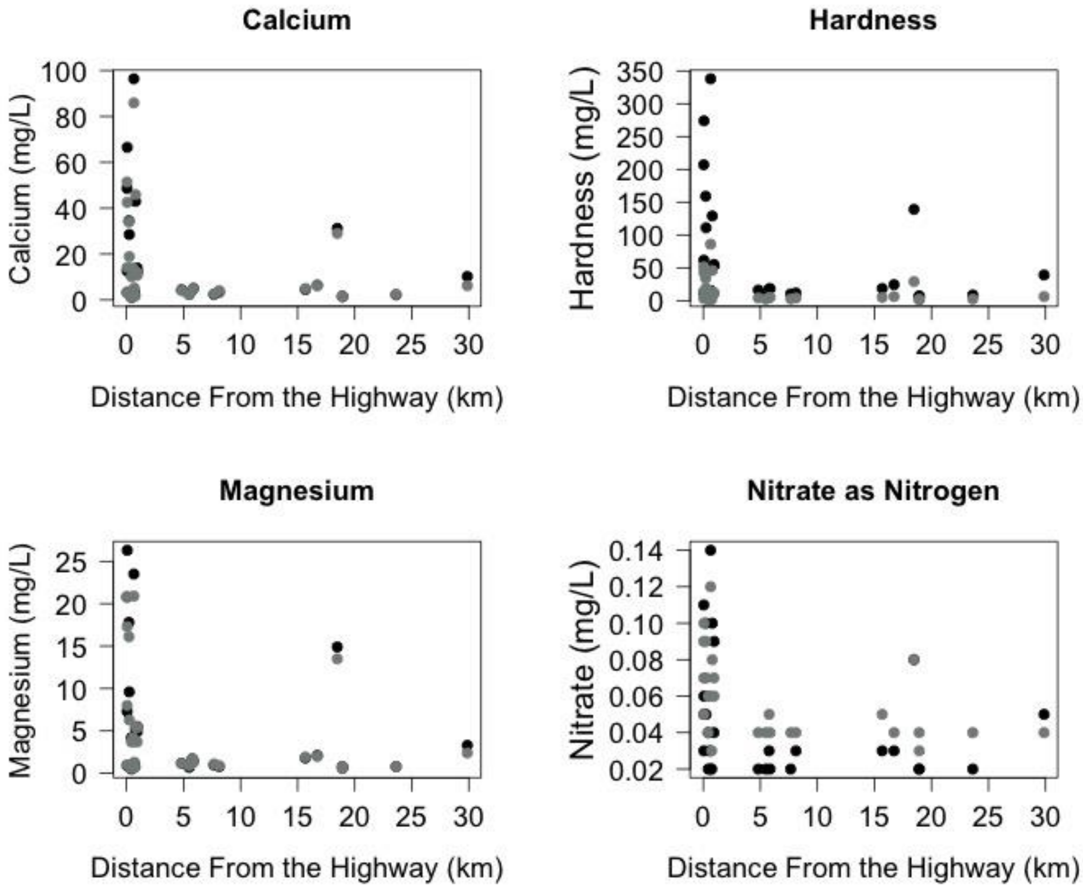
Distance (km)	Site	Latitude	Longitude	Mn	Mo	Ni	Rb	Se	Ag	Sr	Tl	Ti	U	V	Zn
4.82	FM-19	67 10'30.79"	135 29'35.36"	31.60	0.20	4.50	0.30	0.50	0.10	14.70	0.10	0.90	0.10	0.80	11.80
5.48	DEMP LK 3	67 17'5.09"	135 24'0.64"	16.70	0.10	3.20	0.40	0.50	0.10	8.50	0.10	1.10	0.10	0.80	7.10
5.77	FM-20	67 11'32.88"	135 8'56.10"	26.80	0.20	3.60	0.60	0.50	0.10	18.70	0.10	2.60	0.10	1.90	9.70
5.86	DEMP LK 4	67 17'25.85"	135 22'53.96"	34.50	0.30	4.00	0.40	0.50	0.10	18.00	0.10	1.00	0.10	1.10	7.70
7.66	FM-27	67 18'32.22"	135 13'39.74"	20.40	0.20	3.90	0.50	0.50	0.10	12.30	0.10	0.70	0.10	0.60	9.30
8.12	FM-21	67 9'48.76"	135 21'21.04"	38.00	0.10	2.30	0.20	0.50	0.10	10.50	0.10	0.40	0.10	0.30	8.30
15.68	FM-23	67 5'57.17"	135 12'2.85"	20.10	0.20	3.40	0.40	0.50	0.10	15.70	0.10	0.60	0.10	0.40	5.80
16.72	FM-30	67 23'21.50"	135 18'14.30"	7.10	0.10	1.60	0.20	0.50	0.10	19.60	0.10	0.30	0.10	0.20	5.00
18.47	FM-29*	67 23'53.18"	135 25'32.69"	34.20	0.10	7.10	1.50	0.50	0.10	96.30	0.10	0.30	0.10	0.10	9.40
18.92	FM-28	67 23'11.17"	135 32'56.08"	29.60	0.20	3.50	0.40	0.50	0.10	10.20	0.10	1.40	0.10	1.40	11.50
18.93	FM-24	67 4'3.98"	135 21'41.66"	27.70	0.10	4.40	0.30	0.50	0.10	7.80	0.10	1.10	0.10	0.90	11.60
23.62	FM-06	67 30'20.23"	135 18'35.33"	31.20	0.10	1.80	0.50	0.50	0.10	8.60	0.10	0.60	0.10	0.50	5.00
29.87	FM-31	67 30'4.01"	135 21'59.31"	48.70	0.10	2.00	0.50	0.50	0.10	33.90	0.10	0.30	0.10	0.10	5.00

Appendix II

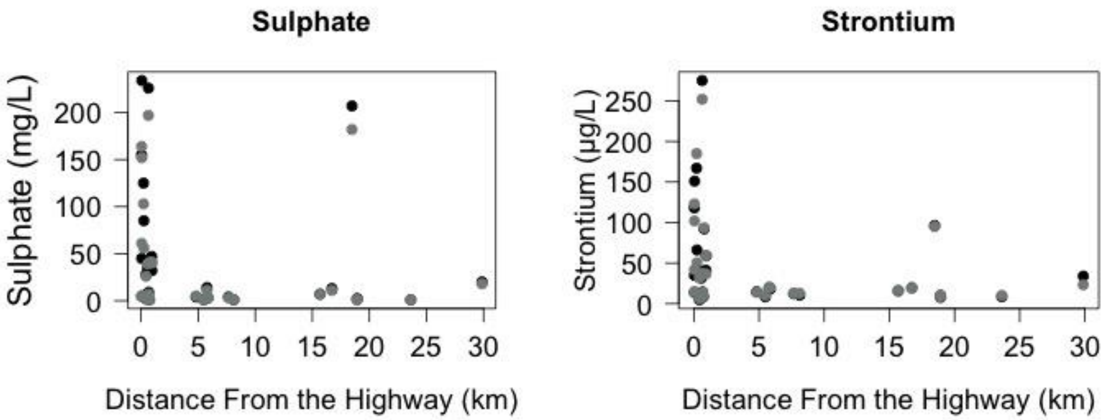
Water Chemistry Full Plots



Changes in alkalinity, conductivity, total dissolved solids (TDS) and pH with varying distance from the Dempster Highway. All variables decrease with increasing distance from the highway corridor. Lakes within 1 km of the Dempster Highway show much higher values than lakes that are farther away. The conductivity and TDS points at ~18 km (lake FM29) have a retrogressive thaw slump on the north side of the lake shoreline. The grey dots represent 2014 data, while the black represents 2015 data. Between 2014 and 2015 there is a slight increase in alkalinity, conductivity, TDS and pH overall.



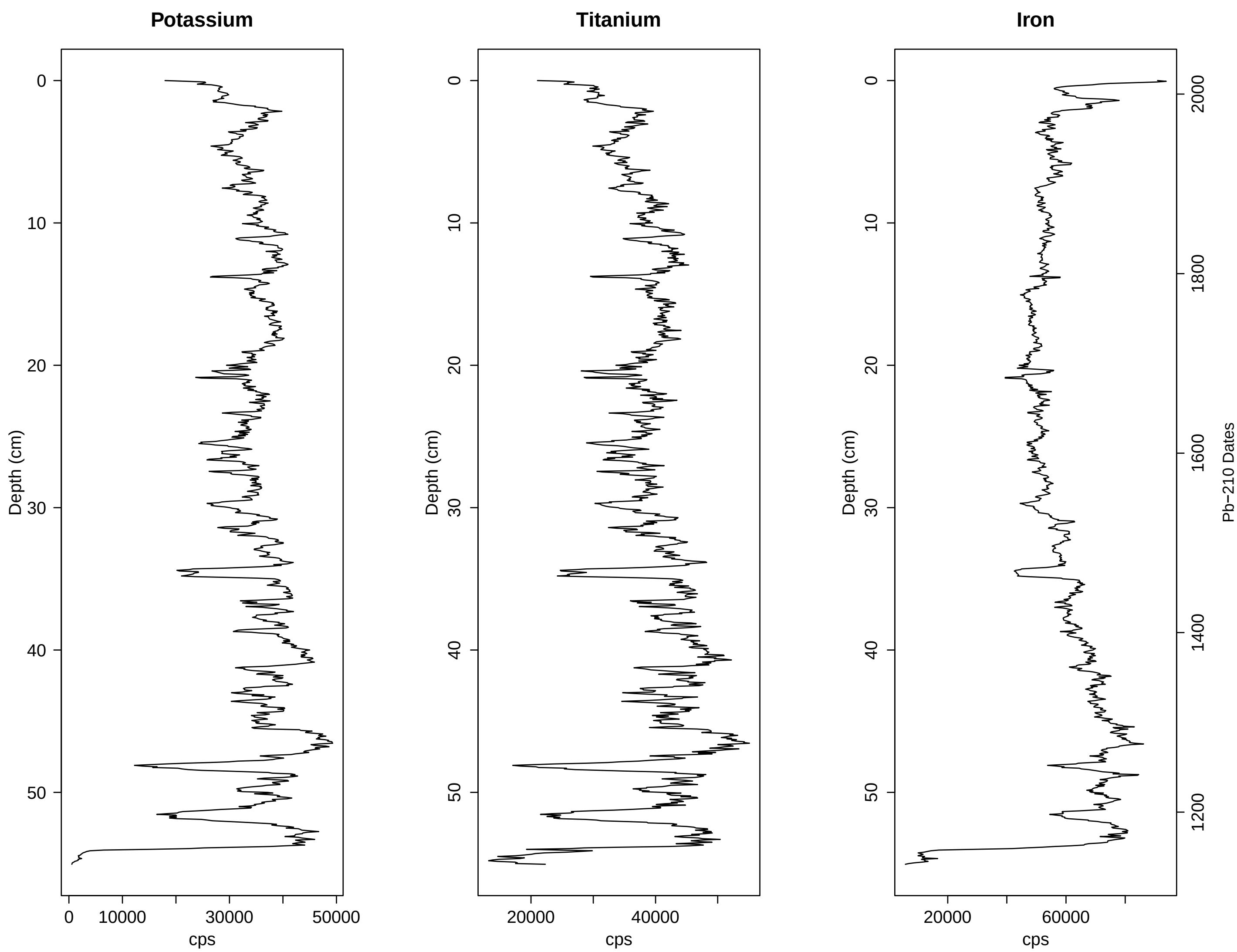
Changes in calcium (Ca^{2+}), hardness, magnesium (Mg^{2+}) and Nitrate along a transect from the Dempster Highway. All variables have decreasing trends with increasing distance from the highway corridor. Lakes within 1 km of the Dempster Highway show much higher values than those lakes that are farther away. The Ca^{2+}, hardness, Mg^{2+} and NO_3 points at ~18 km (lake FM29) have a retrogressive thaw slump on the north side of the lake shoreline. The grey dots represent 2014 data, while the black represents 2015 data. Between 2014 and 2015 there is a slight increase in Ca^{2+}, hardness and Mg^{2+}.



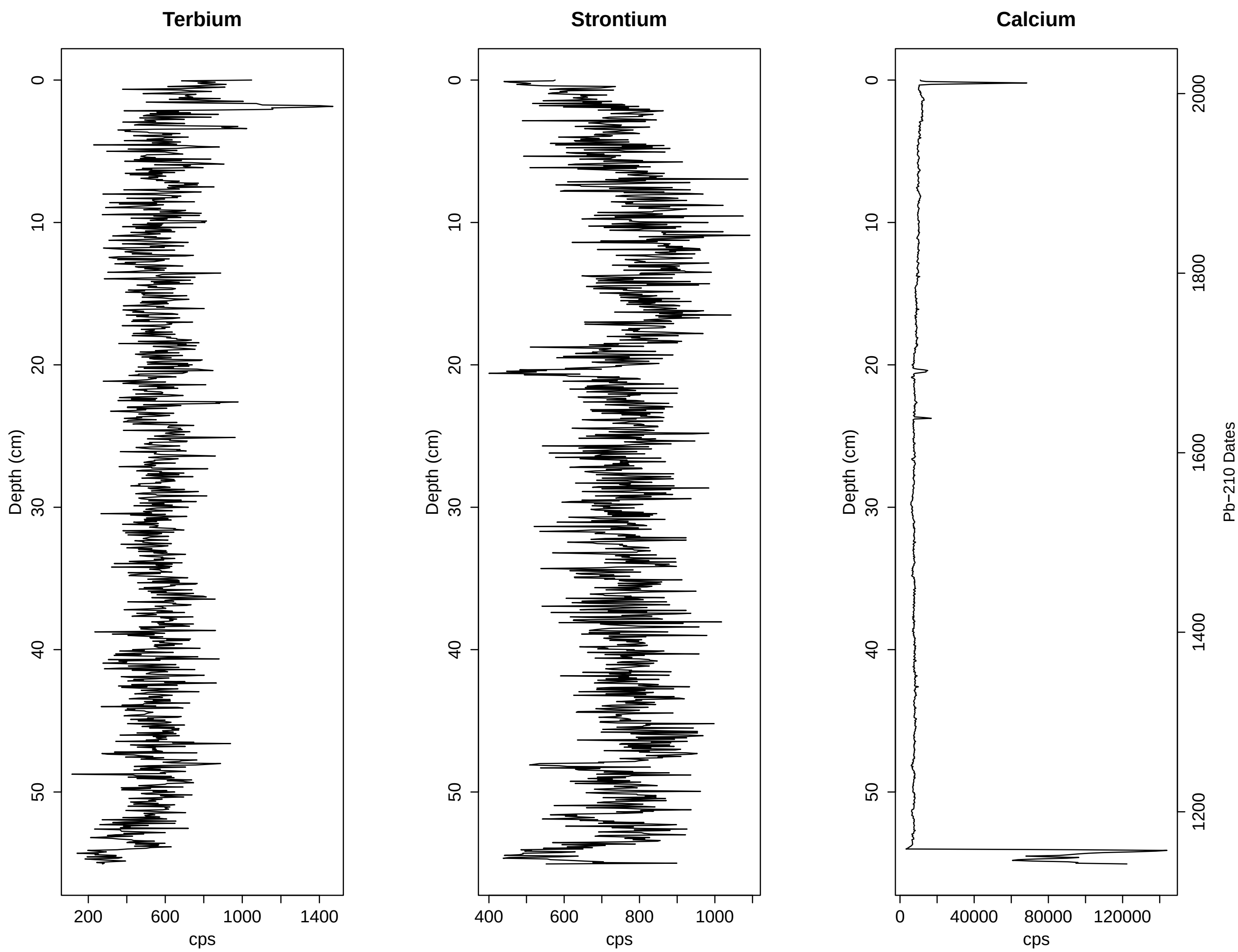
Changes sulphate (SO_4^{-2}) and strontium (Sr^{2+}) along a transect of varying distance from the Dempster Highway. Both variables have decreasing trends with increasing distance from the highway corridor. Lakes within 1 km of the Dempster Highway show much higher values than those lakes that are farther away. SO_4^{-2} and Sr^{2+} points at ~18 km (lake FM29) have a retrogressive thaw slump on the north side of the lake shoreline. The grey dots represent 2014 data, while the black represents the 2015 data. Between 2014 and 2015 there is a slight increase in SO_4^{-2} and Sr^{2+}.

Appendix III
Depmster Highway ITRAX X-ray fluorescence Core Scanning System Full Plots For FM02, FM04 and FM06.

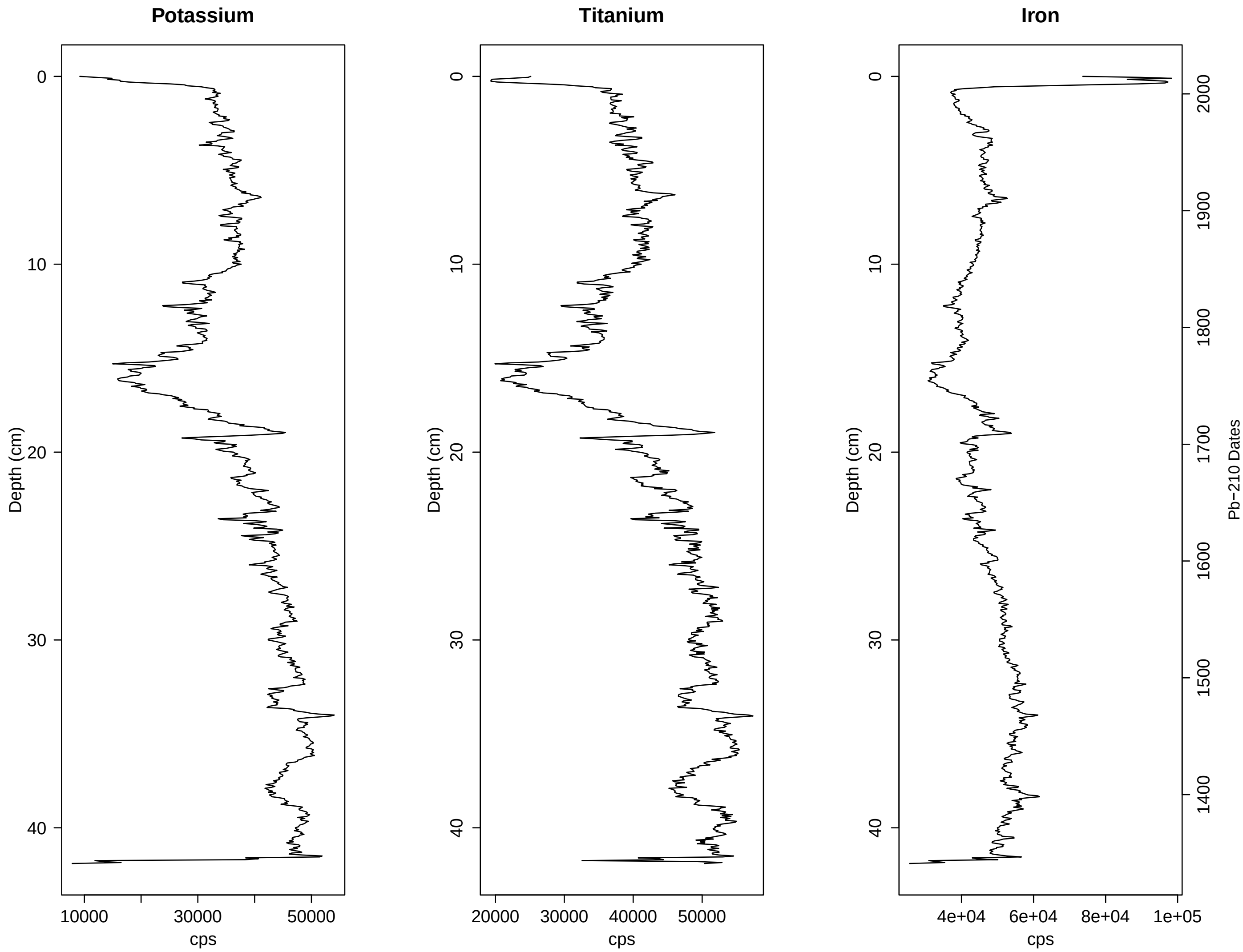
a) FM02 full elemental plots for potassium, titanium, and iron



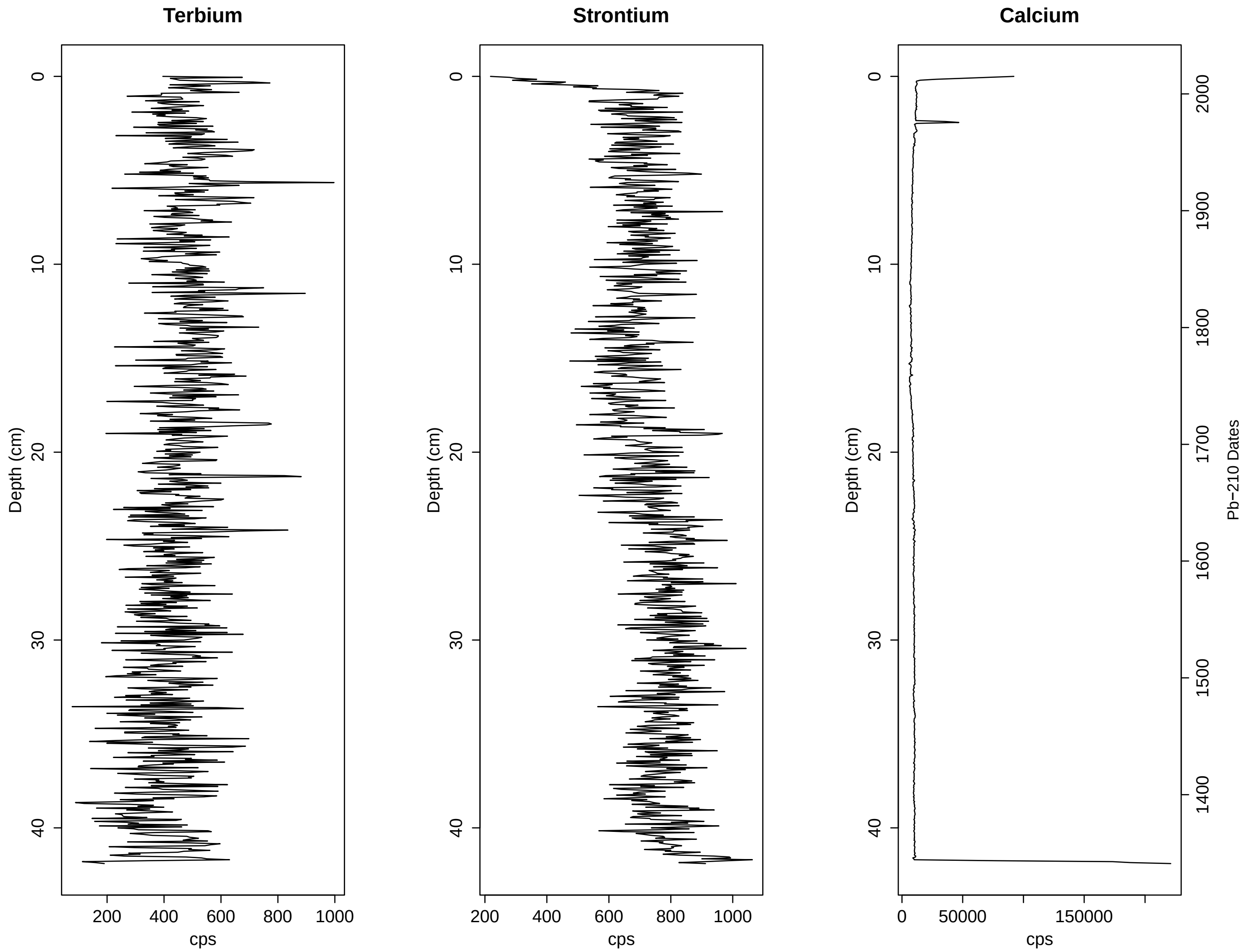
b) FM02 full elemental plots for terbium, strontium and calcium



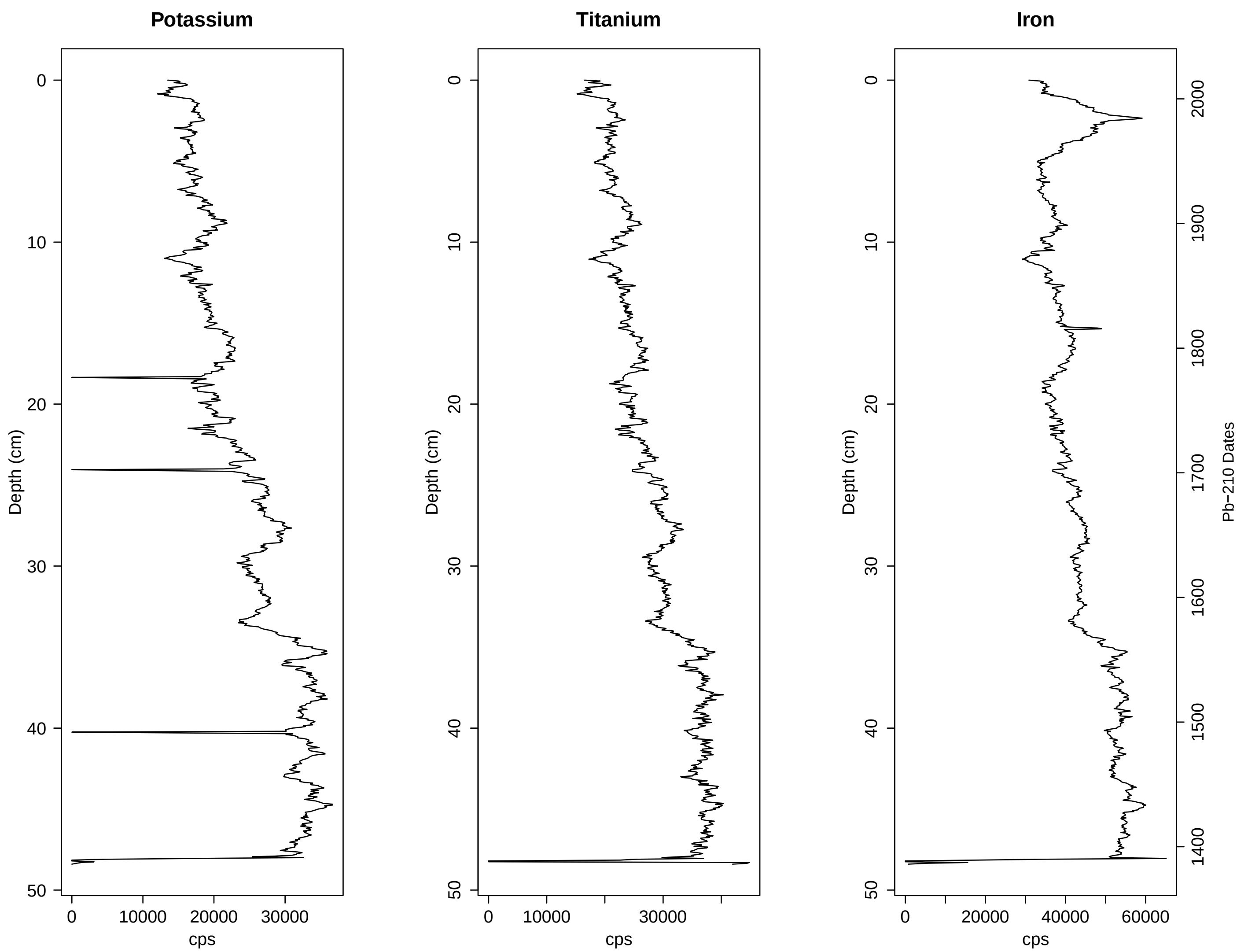
c) FM04 full elemental plots for potassium, titanium and iron



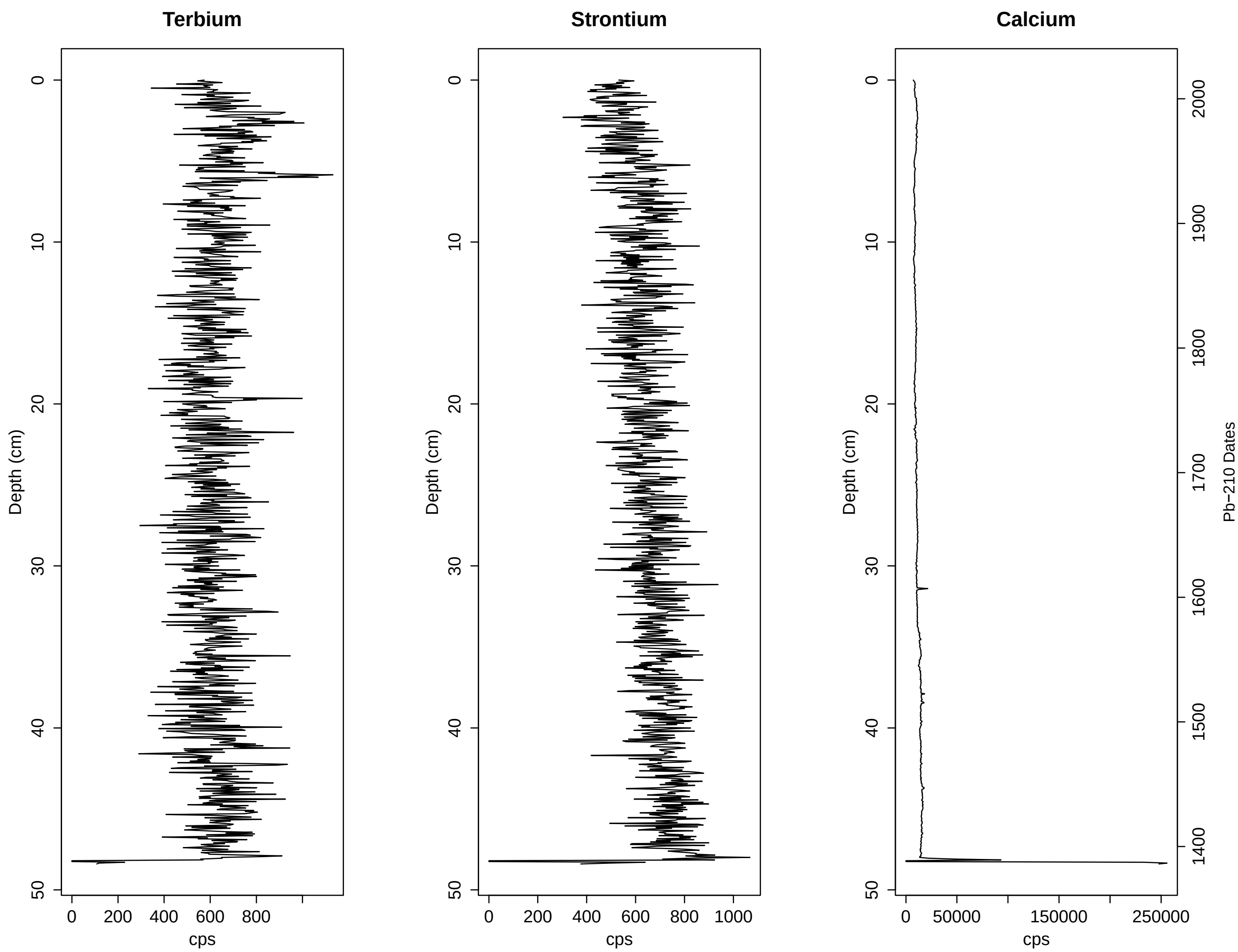
d) FM04 full elemental plots for terbium, strontium and calcium



e) FM06 full elemental plots for potassium, titanium and iron



f) FM06 full elemental plots for terbium, strontium and calcium



Appendix IV

The Impact of construction of the Dempster Highway and production of Road Dust on Algal Palynomorphs in small lakes adjacent to the highway

NPP Processing and Counts

The processing of sediment for the analysis of algal palynomorphs was undertaken by Caitlin Garner with the assistance of the candidate (Rebecca Gunter). Caitlin Garner carried out all identifications and counts of the algal palynomorph data. Rebecca Gunter provided the interpretations of the algal palynomorph data.

Sediments were processed for algal palynomorphs with a slightly modified procedure from Faegri and Iverson (1975), which is typically used to process Quaternary lacustrine sediments. First, the volume of sediment (2.5 mL) was determined by liquid displacement (distilled water) (Bennett and Willis, 2001). The samples were then centrifuged and water was poured off; centrifuging occurred after each addition of liquid. At this time 25 mL of 0.02% sodium hexametaphosphate was added to each sample in order to disaggregate the sediment, but no acetolysis treatment was performed (Riddick et al., 2016). The remaining processes followed standard procedures: carbonates were dissolved using hot 10% hydrochloric acid (HCl) and the silicates dissolved using hot hydrofluoric acid (HF) (48%). A *Lycopodium clavatum* tablet (batch 1031, 20848 +/- 3457) was added prior to the initial treatment step to help quantify the concentration of algal palynomorphs during counting (Benninghoff, 1962). A hot water bath (not boiling) was used throughout the acid treatment, but the exposure time was less than 30 minutes. Finally, residues were sieved using a 10μm *Nitex* mesh and the slides were then mounted using glycerin jelly.

The NPP were identified using published sources including Coesel and Meesters

(2007), Wehr and Sheath (2003), John et al. (2002), Beyens and Meisterfeld (2001) and Komárek and Jankovská (2001) by Caitlin Garner (BSc). For each sample, NPP were enumerated and identified to a total of 50 *Lycopodium clavatum* spores in each sample. Chambers et al. (2011) state that certain spores may be too time consuming to count, in which case one should count to a known number of added exotic spores or pollen. Counting to 50 *Lycopodium clavatum* spores was employed to ensure there was no bias in the counts and to standardize the sampling efforts (Stockmarr, 1971).

Along with the overall counts for NPP, the concentration of each sample was calculated using the following equation modified from Bennett and Willis (2001):

$$\mathbf{C_p} = \frac{\boldsymbol{\Sigma\,(P)(N_L) \div \Sigma C_L}}{\boldsymbol{V}} \qquad \textbf{(4)}$$

where,

C_p = concentration

ΣP = the sum of the counted NPP in the sample

N_L = the number of markers (in this case *Lycopodium clavatum* spores) added to the sample

ΣC_L = the number of *Lycopodium clavatum* spores counted in the sample (50)

V = the volume of the sample (2.5 ml)

Raw NPP counts

These are the raw NPP counts that were taken for the impacted core, FM02.

NAME	1cm	2cm	3cm	4cm	5cm	6cm	7cm	8cm	14cm	20cm	26cm	32cm	38cm	44cm	50cm
Botryococcus braunii	1.0	3.0	0.0	5.0	7.0	0.0	0.0	0.0	1.0	1.0	0.0	2.0	1.0	1.0	0.0
C. botrytis	0.5	0.0	1.0	2.5	2.0	0.0	1.5	4.5	4.5	3.5	0.0	1.5	5.0	5.0	5.0
C. depressum	1.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0
C. formusolum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.5
C. hexalobum var. minus	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C. meneghini	0.0	0.0	0.0	0.5	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0
C. protractum	1.5	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.5	0.0	0.0
C. protrytis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0
C. pseudopyramidatum	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C. pyramidatum	18.5	29.5	2.0	22.0	14.5	6.0	3.5	5.0	2.0	2.0	0.0	1.5	1.5	0.5	2.5
C. turpinii	0.5	0.0	0.0	0.5	0.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cosmarium spp.	5.5	2.0	4.0	5.5	1.0	4.0	2.5	1.0	0.5	0.5	0.5	2.0	4.0	0.5	2.5
E. ansatum	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
E. bidelta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
E.bBidentatum	0.0	0.0	1.0	2.0	0.5	0.5	0.0	0.5	0.5	3.0	6.5	1.0	6.0	4.5	3.0
E. cuneatum	0.0	0.0	0.0	0.5	0.5	0.5	0.0	0.5	2.0	2.0	3.5	1.0	1.5	1.0	1.0
E. didelta	0.0	0.0	0.5	0.0	0.0	0.0	1.0	0.5	6.5	3.5	4.0	1.5	1.0	0.5	0.0
E. oblongum	0.0	0.5	0.0	0.0	0.0	0.5	0.0	1.0	1.5	0.5	0.0	0.0	2.0	0.0	0.0
E. pseudotuddalense	0.0	0.5	4.0	10.5	13.5	13.5	3.5	3.0	0.0	2.5	0.5	1.5	1.5	2.5	1.5
Euastrum spp.	0.0	0.0	1.0	0.5	1.0	0.0	1.0	2.0	2.0	2.0	1.5	0.5	1.0	1.5	0.0
Pediastrum spp.	7.0	9.0	0.0	27.0	24.0	11.5	1.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S. anatinum	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S. bieneanum	0.0	0.0	0.5	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

S. gracile	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	7.5	2.0	2.0	4.5	1.0	0.0
S. muticum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	2.5	0.0	0.5
Staurastrum spp.	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.5	0.0	0.0	0.0	0.0
Lycopodium clavatum	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Sphagnum	4.0	6.0	14.0	0.0	0.0	10.0	6.0	3.0	-	-	-	-	-	-	-

Shannon Diversity Index Spreadsheet

NAME	1cm	Pi	lnPi	pi * lnpi		2cm	Pi	lnPi	pi * lnpi		3cm	Pi	lnPi	pi * lnpi		4cm	Pi	lnPi	pi * lnpi
Botryococcus braunii	1.0	0.025641026	-3.663561646	0.093937478		3.0	0.0674157	-2.69688	0.181811926		0.0	0	0	0		5.0	0.06451613	-2.74084	0.17682839
C. botrytis	0.5	0.012820513	-4.356708827	0.055855241		0.0	0	0	0		1.0	0.05128205	-2.9704145	0.15232895		2.5	0.03225806	-3.4339872	0.11077378
C. depressum	1.0	0.025641026	-3.663561646	0.093937478		0.0	0	0	0		1.5	0.07692308	-2.5649494	0.1973038		0.0	0	0	0
C. formusolum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
C. hexalobum var. minus	0.0	0	0	0		0.0	0	0	0		1.0	0.05128205	-2.9704145	0.15232895		0.0	0	0	0
C. meneghini	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.5	0.00645161	-5.0434251	0.03253823
C. protractum	1.5	0.038461538	-3.258096538	0.125311405		0.0	0	0	0		0.0	0	0	0		1.0	0.01290323	-4.3502779	0.05613262
C. protrytis	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
C. pseudopyramidatum	3.5	0.08974359	-2.410798678	0.216353727		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
C. pyramidatum	18.5	0.474358974	-0.745790914	0.353772613		29.5	0.6629213	-0.4111	0.272526254		2.0	0.1025641	-2.2772673	0.23356588		22.0	0.28387097	-1.2592355	0.3574604
C. turpinii	0.5	0.012820513	-4.356708827	0.055855241		0.0	0	0	0		0.0	0	0	0		0.5	0.00645161	-5.0434251	0.03253823
Cosmarium spp.	5.5	0.141025641	-1.958813554	0.276242937		2.0	0.0449438	-3.10234	0.139431102		4.0	0.20512821	-1.5841201	0.32494771		5.5	0.07096774	-2.6455298	0.18774728
E. ansatum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
E. bidelta	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
E.bidentatum	0.0	0	0	0		0.0	0	0	0		1.0	0.05128205	-2.9704145	0.15232895		2.0	0.02580645	-3.6571308	0.09437757
E. cuneatum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.5	0.00645161	-5.0434251	0.03253823
E. didelta	0.0	0	0	0		0.0	0	0	0		0.5	0.02564103	-3.6635616	0.09393748		0.0	0	0	0
E. oblongum	0.0	0	0	0		0.5	0.011236	-4.48864	0.050434117		0.0	0	0	0		0.0	0	0	0
E. pseudotuddalense	0.0	0	0	0		0.5	0.011236	-4.48864	0.050434117		4.0	0.20512821	-1.5841201	0.32494771		10.5	0.13548387	-1.9989027	0.27081907
Euastrum spp.	0.0	0	0	0		0.0	0	0	0		1.0	0.05128205	-2.9704145	0.15232895		0.5	0.00645161	-5.0434251	0.03253823
Pediastrum spp.	7.0	0.179487179	-1.717651497	0.308296423		9.0	0.2022472	-1.59826	0.323244528		0.0	0	0	0		27.0	0.3483871	-1.0544411	0.36735366
S. anatinum	0.0	0	0	0		0.0	0	0	0		1.0	0.05128205	-2.9704145	0.15232895		0.0	0	0	0
S. bieneanum	0.0	0	0	0		0.0	0	0	0		0.5	0.02564103	-3.6635616	0.09393748		0.0	0	0	0
S. gracile	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
S. muticum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
Staurastrum spp.	0.0	0	0	0		0.0	0	0	0		2.0	0.1025641	-2.2772673	0.23356588		0.0	0	0	0
Ni	39.0		H	1.579562544	Ni	44.5		H	1.017882043	Ni	19.5		H	2.26385067	Ni	77.5		H	1.75164567

NAME	5cm	Pi	lnPi	pi * lnpi	6cm	Pi	lnPi	pi * lnpi	7cm	Pi	lnPi	pi * lnpi	8cm	Pi	lnPi	pi * lnpi
Botryococcus braunii	7.0	0.109375	-2.2129729	0.24204391	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0
C. botrytis	2.0	0.03125	-3.4657359	0.10830425	0.0	0	0	0	1.5	0.10714286	-2.2335922	0.23931345	4.5	0.17647059	-1.7346011	0.30610607
C. depressum	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0
C. formusolum	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0
C. hexalobum var. minus	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0
C. meneghini	0.0	0	0	0	1.0	0.025	-3.6888795	0.09222199	0.0	0	0	0	0.0	0	0	0
C. protractum	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0
C. protrytis	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0
C. pseudopyramidatum	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0
C. pyramidatum	14.5	0.2265625	-1.4847344	0.33638515	6.0	0.15	-1.89712	0.284568	3.5	0.25	-1.3862944	0.34657359	5.0	0.19607843	-1.6292405	0.31945893
C. turpinii	0.0	0	0	0	1.0	0.025	-3.6888795	0.09222199	0.0	0	0	0	1.0	0.03921569	-3.2386785	0.127007
Cosmarium spp.	1.0	0.015625	-4.1588831	0.06498255	4.0	0.1	-2.3025851	0.23025851	2.5	0.17857143	-1.7227666	0.30763689	1.0	0.03921569	-3.2386785	0.127007
E. ansatum	0.0	0	0	0	0.5	0.0125	-4.3820266	0.05477533	0.0	0	0	0	0.0	0	0	0
E. bidelta	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0
E.bidentatum	0.5	0.0078125	-4.8520303	0.03790649	0.5	0.0125	-4.3820266	0.05477533	0.0	0	0	0	0.5	0.01960784	-3.9318256	0.07709462
E. cuneatum	0.5	0.0078125	-4.8520303	0.03790649	0.5	0.0125	-4.3820266	0.05477533	0.0	0	0	0	0.5	0.01960784	-3.9318256	0.07709462
E. didelta	0.0	0	0	0	0.0	0	0	0	1.0	0.07142857	-2.6390573	0.18850409	0.5	0.01960784	-3.9318256	0.07709462
E. oblongum	0.0	0	0	0	0.5	0.0125	-4.3820266	0.05477533	0.0	0	0	0	1.0	0.03921569	-3.2386785	0.127007
E. pseudotuddalense	13.5	0.2109375	-1.5561934	0.32825954	13.5	0.3375	-1.0861898	0.36658905	3.5	0.25	-1.3862944	0.34657359	3.0	0.11764706	-2.1400662	0.25177249
Euastrum spp.	1.0	0.015625	-4.1588831	0.06498255	0.0	0	0	0	1.0	0.07142857	-2.6390573	0.18850409	2.0	0.07843137	-2.5455313	0.19964951
Pediastrum spp.	24.0	0.375	-0.9808293	0.36781097	11.5	0.2875	-1.2465324	0.35837807	1.0	0.07142857	-2.6390573	0.18850409	6.0	0.23529412	-1.446919	0.34045153
S. anatinum	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0	0.5	0.01960784	-3.9318256	0.07709462
S. bieneanum	0.0	0	0	0	1.0	0.025	-3.6888795	0.09222199	0.0	0	0	0	0.0	0	0	0
S. gracile	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0
S. muticum	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0
Staurastrum spp.	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0	0.0	0	0	0
	64.0		H	1.58858189 Ni	40.0		H	1.73556092 Ni	14.0		H	1.80560981 Ni	25.5		H	2.106838

NAME	14cm	Pi	lnPi	pi * lnpi		20cm	Pi	lnPi	pi * lnpi		26cm	Pi	lnPi	pi * lnpi		32cm	Pi	lnPi	pi * lnpi
Botryococcus braunii	1.0	0.04444444	-3.1135153	0.13837846		1.0	0.03508772	-3.3499041	0.11754049		0.0	0	0	0		2.0	0.125	-2.0794415	0.25993019
C. botrytis	4.5	0.2	-1.6094379	0.32188758		3.5	0.12280702	-2.0971411	0.25754365		0.0	0	0	0		1.5	0.09375	-2.3671236	0.22191784
C. depressum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
C. formusolum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
C. hexalobum var. minus	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
C. meneghini	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
C. protractum	0.0	0	0	0		0.5	0.01754386	-4.0430513	0.07093072		0.0	0	0	0		0.0	0	0	0
C. protrytis	0.0	0	0	0		0.0	0	0	0		2.0	0.0952381	-2.3513753	0.2239405		0.0	0	0	0
C. pseudopyramidatum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
C. pyramidatum	2.0	0.08888889	-2.4203681	0.21514383		2.0	0.07017544	-2.6567569	0.18643908		0.0	0	0	0		1.5	0.09375	-2.3671236	0.22191784
C. turpinii	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
Cosmarium spp.	0.5	0.02222222	-3.8066625	0.0845925		0.5	0.01754386	-4.0430513	0.07093072		0.5	0.02380952	-3.7376696	0.08899213		2.0	0.125	-2.0794415	0.25993019
E. ansatum	0.5	0.02222222	-3.8066625	0.0845925		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
E. bidelta	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		1.0	0.0625	-2.7725887	0.1732868
E.bidentatum	0.5	0.02222222	-3.8066625	0.0845925		3.0	0.10526316	-2.2512918	0.23697808		6.5	0.30952381	-1.1727203	0.36298484		1.0	0.0625	-2.7725887	0.1732868
E. cuneatum	2.0	0.08888889	-2.4203681	0.21514383		2.0	0.07017544	-2.6567569	0.18643908		3.5	0.16666667	-1.7917595	0.29862658		1.0	0.0625	-2.7725887	0.1732868
E. didelta	6.5	0.28888889	-1.2417131	0.35871713		3.5	0.12280702	-2.0971411	0.25754365		4.0	0.19047619	-1.6582281	0.31585297		1.5	0.09375	-2.3671236	0.22191784
E. oblongum	1.5	0.06666667	-2.7080502	0.18053668		0.5	0.01754386	-4.0430513	0.07093072		0.0	0	0	0		0.0	0	0	0
E. pseudotuddalense	0.0	0	0	0		2.5	0.0877193	-2.4336134	0.21347486		0.5	0.02380952	-3.7376696	0.08899213		1.5	0.09375	-2.3671236	0.22191784
Euastrum spp.	2.0	0.08888889	-2.4203681	0.21514383		2.0	0.07017544	-2.6567569	0.18643908		1.5	0.07142857	-2.6390573	0.18850409		0.5	0.03125	-3.4657359	0.10830425
Pediastrum spp.	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
S. anatinum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
S. bieneanum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
S. gracile	1.0	0.04444444	-3.1135153	0.13837846		7.5	0.26315789	-1.3350011	0.35131607		2.0	0.0952381	-2.3513753	0.2239405		2.0	0.125	-2.0794415	0.25993019
S. muticum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0		0.5	0.03125	-3.4657359	0.10830425
Staurastrum spp.	0.5	0.02222222	-3.8066625	0.0845925		0.0	0	0	0		0.5	0.02380952	-3.7376696	0.08899213		0.0	0	0	0
	22.5		H	2.12169981	NI	28.5		H	2.20650621	NI	21.0		H	1.88082589	NI	16.0		H	2.40393081

NAME	38cm	Pi	lnPi	pi * lnpi		44cm	Pi	lnPi	pi * lnpi		50cm	Pi	lnPi	pi * lnpi
Botryococcus braunii	1.0	0.03125	-3.4657359	0.10830425		1.0	0.05	-2.9957323	0.14978661		0.0	0	0	0
C. botrytis	5.0	0.15625	-1.856298	0.29004656		5.0	0.25	-1.3862944	0.34657359		5.0	0.28571429	-1.252763	0.35793228
C. depressum	0.0	0	0	0		0.5	0.025	-3.6888795	0.09222199		1.0	0.05714286	-2.8622009	0.16355434
C. formusolum	0.0	0	0	0		1.0	0.05	-2.9957323	0.14978661		0.5	0.02857143	-3.5553481	0.10158137
C. hexalobum var. minus	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
C. meneghini	0.0	0	0	0		0.5	0.025	-3.6888795	0.09222199		0.0	0	0	0
C. protractum	0.5	0.015625	-4.1588831	0.06498255		0.0	0	0	0		0.0	0	0	0
C. protrytis	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
C. pseudopyramidatum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
C. pyramidatum	1.5	0.046875	-3.0602708	0.14345019		0.5	0.025	-3.6888795	0.09222199		2.5	0.14285714	-1.9459101	0.27798716
C. turpinii	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
Cosmarium spp.	4.0	0.125	-2.0794415	0.25993019		0.5	0.025	-3.6888795	0.09222199		2.5	0.14285714	-1.9459101	0.27798716
E. ansatum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
E. bidelta	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
E.bidentatum	6.0	0.1875	-1.6739764	0.31387058		4.5	0.225	-1.4916549	0.33562235		3.0	0.17142857	-1.7635886	0.30232947
E. cuneatum	1.5	0.046875	-3.0602708	0.14345019		1.0	0.05	-2.9957323	0.14978661		1.0	0.05714286	-2.8622009	0.16355434
E. didelta	1.0	0.03125	-3.4657359	0.10830425		0.5	0.025	-3.6888795	0.09222199		0.0	0	0	0
E. oblongum	2.0	0.0625	-2.7725887	0.1732868		0.0	0	0	0		0.0	0	0	0
E. pseudotuddalense	1.5	0.046875	-3.0602708	0.14345019		2.5	0.125	-2.0794415	0.25993019		1.5	0.08571429	-2.4567358	0.21057735
Euastrum spp.	1.0	0.03125	-3.4657359	0.10830425		1.5	0.075	-2.5902672	0.19427004		0.0	0	0	0
Pediastrum spp.	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
S. anatinum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
S. bieneanum	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
S. gracile	4.5	0.140625	-1.9616585	0.27585823		1.0	0.05	-2.9957323	0.14978661		0.0	0	0	0
S. muticum	2.5	0.078125	-2.5494452	0.1991754		0.0	0	0	0		0.5	0.02857143	-3.5553481	0.10158137
Staurastrum spp.	0.0	0	0	0		0.0	0	0	0		0.0	0	0	0
	32.0		H	2.33241363	NI	20.0		H	2.19665255	NI	17.5		H	1.95708485

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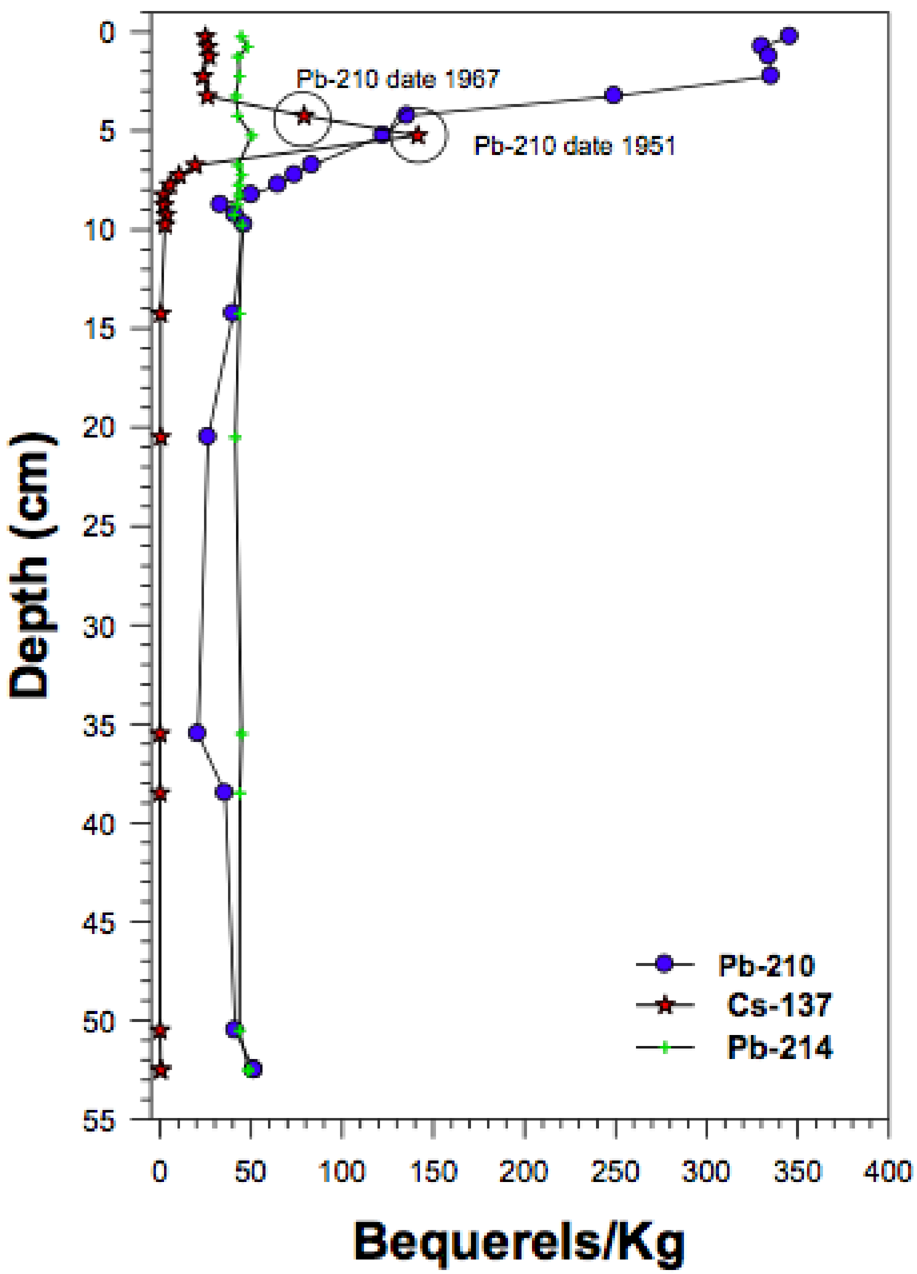
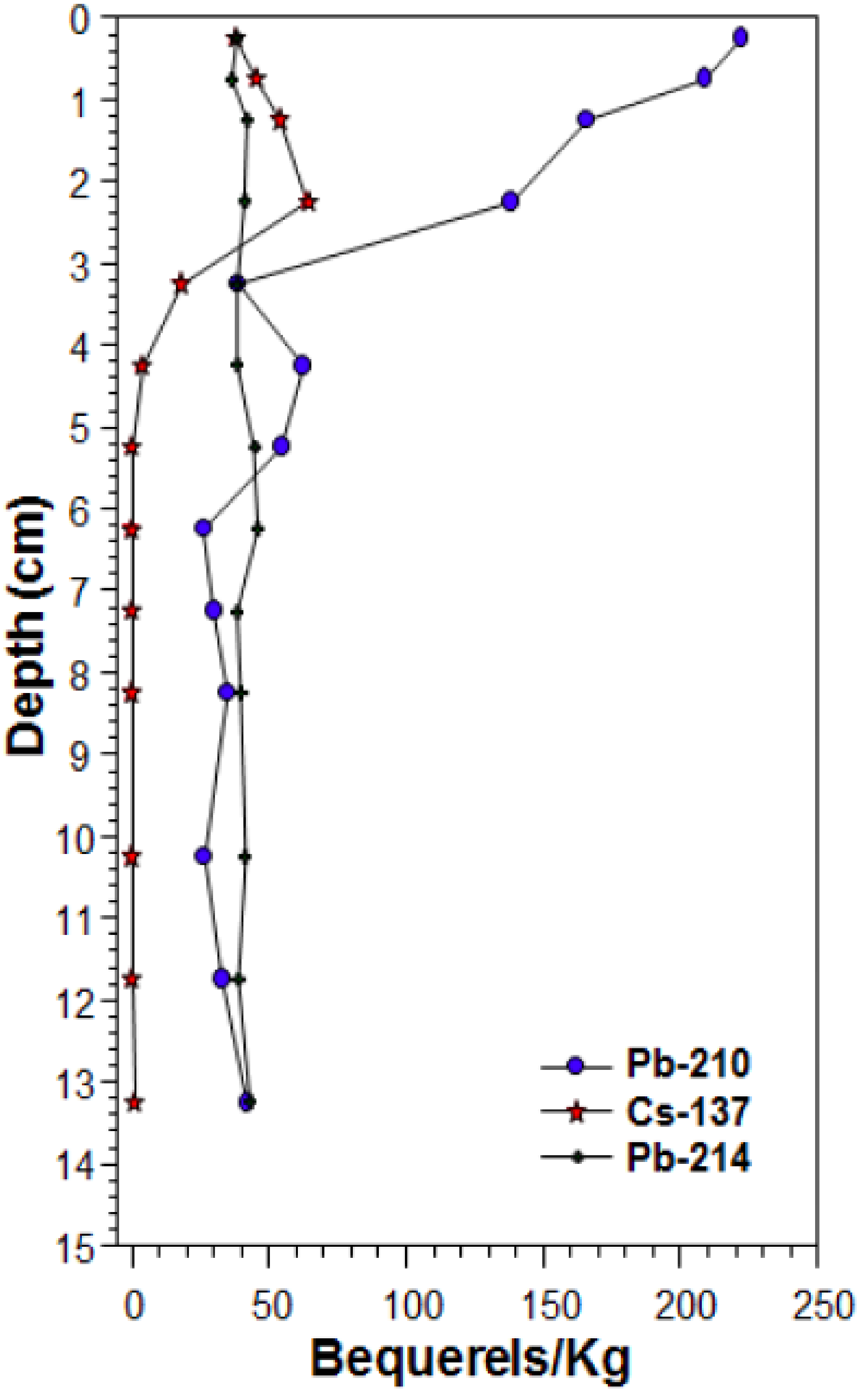
Appendix V

Pb^{210} Dating Profiles

Lake Sediment Core FM02 Pb-210 Dating Profile



Lake Sediment Core FM04 Pb-210 Dating Profile



Lake Sediment Core FM06 Pb-210 Dating Profile